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Review

Satellite based remote sensing of weather and climate: recent achievements and future perspectives

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ABSTRACT: Spaceborne remote sensing provides valuable information about the state of the Earth-atmosphere system and its components in an area-wide and continuous manner. Over the past 50 years a range of satellite platforms carrying many different sensors has been constructed to monitor atmospheric parameters used in meteorological and climatological studies, and the information retrieved from satellite-based sensors has greatly enhanced our understanding of the processes and dynamics within the Earth-atmosphere system. The present paper gives an overview of existing satellites and sensors, together with the developed algorithms to retrieve meteorological and climatological parameters. Furthermore, it gives an outlook on new systems planned for the near future. Copyright © 2011 Royal Meteorological Society

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1. Introduction

Satellite systems provide a unique opportunity to monitor Earth-atmosphere system processes and parameters continuously. In view of the great benefit provided by spaceborne Earth-atmosphere remote sensing, there were strong efforts to construct Earth observing satellite systems in the past. Satellite based observations of the Earth and the atmosphere started with the first meteorological satellite, the Television InfraRed Observation Satellite (TIROS-1), launched in 1960. During the following decades several satellite systems with different sensors provided data for a wide range of atmospheric parameters that enhanced our understanding of Earth-atmosphere processes and dynamics. Nowadays, operational satellite systems provide invaluable measurements of atmospheric parameters at regular intervals on a global scale. Smith *et al*. (1986) and Kidder and Vonder Haar (1995) give an overview of Earth-atmosphere observing satellite systems. More recently, Kidd *et al*. (2009) outlined the status of satellite based meteorological and climatological research.

The present paper gives an overview of existing satellite systems and the corresponding retrieval techniques to derive the desired meteorological and climatological parameters. It starts with a review of existing platforms and sensors. After the review of existing satellite systems and retrieval algorithms, satellite missions planned and approved for the near future will be introduced. This is followed by an overview of existing retrieval algorithms, which is structured by the different measurement parameters.

2. Satellite systems

2.1. Past and current satellite systems

Satellite based Earth-atmosphere observations exploit geostationary (GEO) and low-Earth-orbiting (LEO) satellite systems, providing data in different spatial and temporal resolutions.

GEO satellite systems circulate the Earth at an altitude of about 36 000 km above the equator. Their orbital period is 24 h. Therefore, they appear to be stationary above a certain point above the equator, which enable observations with a high temporal resolution of 15 or 30 min. Operational geostationary platforms are the workhorses of meteorological nowcasting applications and are growing increasingly important for climate research due to the long time series of GEO data globally available.

Operational polar orbiting platforms (LEO) are complementing the GEO system in the global weather satellite system. They are frequently used to transfer sensors from

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experimental missions into operational use, which in a next step, if technically and financially possible, might become candidates for next generation GEO systems. Table S1 gives an overview of past and current Earth-atmosphere observing satellite systems.

2.2. Future perspectives of satellite meteorology

2.2.1. *Geostationary platforms*

Future GEO missions are primarily focusing on serving the NWP and the climate research communities by striving for improvements of the systems while at the same time warranting data and product continuity. Improvements are concerned for:

- the spatial resolution, e.g. for local nowcasting and to capture subpixel atmospheric phenomena from the GEO orbit;
- the spectral and radiometric (e.g. the signal to noise ratio) resolution to allow for new products and to boost the accuracy of hitherto developed products to the requirements of data assimilation in NWP models, and,
- the temporal resolution to observe atmospheric phenomena with rapid life cycles.

Depending on the history of the specific satellite programmes, the operating agencies are currently developing second or third generation GEO missions which are listed in Table I. Generally, all programmes continue to focus on passive instruments and mainly two proven sensor families: (1) multispectral narrow and broad band imagers to retrieve data on radiation balance, clouds, aerosol, cloud and water vapour (WV) motion, winds, land and sea surface temperatures (LST/SST) as well as Earth's snow and ice cover, and, (2) atmospheric sounding capabilities to retrieve vertical profiles, mainly of temperature and humidity, but also water vapour winds and trace gas information. For the third generation imagers (Flexible Combined Imager (FCI) on Meteosat Third Generation (MTG), partly also for Advanced Baseline Imager (ABI) on GOES-R/Himawari-8), additional bands will be introduced as a heritage of LEO missions as e.g. MODIS: 0.444 and 0.510 μm (aerosol, ocean colour, phytoplankton), 0.910 μm (atmospheric water vapour), 1.375 μm (cirrus clouds) and 2.260 μm (aerosol). Rapid scan capabilities will be offered as well. Next generation GEO satellites will include sounding capabilities for the first time, or change from narrow-band channel IR radiometer solutions to more complex systems as spectrometer technology to improve accuracy and vertical resolution of the products develops. An IASI-like (Infrared Atmospheric Sounding Interferometer) on LEO MetOP (see Prunet *et al*., 1998; Blumstein *et al*., 2004) system, the Interferometric Infrared Sounder (IIS), is intended for launch on board the Chinese FY-4 GEO mission. A major improvement will be the 10 channel Michelson Fourier Transform spectrometer on MTG which will provide hyper-spectral sounding information in two bands, a long and a mid wave IR region with a high spatial resolution of 4 km every half hour (Stuhlmann *et al*., 2005). As a development of LEO instruments such as AIRS (Atmospheric Infra-red Sounder on Aqua), the main challenge for a transfer to a GEO system is to cope with the limitations due to diffraction which might in the worst case produce errors of up to 1 K in sensitive bands (Grandell and Stuhlmann, 2007). A new sensor type which shall be added to Meteosat and GOES third generation (MTG-LI (Lightning Imager)/GOES-R – GLM (Geostationary Lightning Mapper)) and to the Chinese second generation FY-4 satellites is devoted to the detection and nowcasting of lightning, also used as a proxy for severe convective weather and the production of NO_x. All three future missions will rely on measurements in the ionized oxygen emission band at 777.4 nm (for the general technologies refer to Koshak *et al*., 2000). Another novel feature will be the GEO missions targeting atmospheric chemistry. The first spectrometer sensor (0.4 nm resolution) will be installed on board MTG as a development of EPS GOME and ENVISAT SCIAMACHY. It will be dedicated to air quality surveillance regarding emission plumes, aerosols and atmospheric gases (e.g. O_3, NO_2, SO_2, H_2CO). Gas retrieval is mainly conducted in the UV (290–400 nm) region while cloud and aerosol information is analysed in the oxygen A-Band region (755–775 nm). For further information on technology and physical background the reader may refer to Bovensmann *et al*. (1999). As not yet specified, the Korean Meteorological Agency (KMA), (a new player in the group of GEO mission operators), is planning a second GEO atmospheric chemistry mission with its Trace Gas Monitor (TBC) on COMS-FO B (Communication, Ocean and Meteorological Satellite), launch projected for 2018. To date, passive microwave (MW) instruments, which are a backbone for rainfall retrieval techniques, are restricted to LEO missions. This is due to the weak emitted MW signal of the Earth-atmosphere system which is a challenge to detect at GEO flight level (e.g. Joyce *et al*., 2004). The first MW instrument in Geostationary Orbit is planned to fly on China's FY-4 M mission with the Microwave Sounder (GEO-MWRI). Even though the instrument is not yet defined it can be expected that it resembles the spectral characteristics of the Micro-Wave Radiation Imager (MWRI) currently flown on the second generation LEO FY-3 mission (Zhang *et al*., 2006). The third generation GOES-R series will additionally provide instruments for observation of space weather with Space Environment *In-Situ* Suite (SEISS), EUV and X-Ray Irradiance Sensors (EXIS) and the Solar Ultraviolet Imager (SUVI), and for measurements of the Earth's geomagnetic field with Magnetometer (MAG) (Krimchansky *et al*., 2004).

2.2.2. *Low Earth orbit platforms*

As stressed for GEO systems, next generation LEO-missions also pursue the improvement of the spatial, spectral and radiometric resolution and thus an improvement of operational products for nowcasting and

Table I. Major approved and planned next generation GEO missions.

Mission (agency), *orbit*	Sensor	Technology	Launch[a]	Priority products	Improvement
FY-4 O (CMA/NSMC) *China*	(1) Multi-channel Scan Imaging Radiometer (MCSI) (2) Interferometric Infrared Sounder (IIS) (3) Lightning Mapper (LM)	(1) 12-channel VIS/IR imager (0.55–13.8 μm), $x = 1–4$ km (2) IR spectrometer/interferometer (4.44–6.06 and 8.85–14.6 μm); $x = 8$ (later 4) km (3) CCD camera (777.4 nm, O_2); $x = 10$ km	2015	Cloud properties (1) Cloud and WV motion winds (1) Radiation components (1) Rainfall rate (1) Temperature/humidity profiles (2) Profiles of WV motion winds (2)	Three-axis stabilization More powerful imager and lightning mapper Sounding capability
FY-4 M (CMA/NSMC) *China*	(1) MicroWave Radiation Imager (GEO-MWRI)	(1) To be defined; current MWRI on LEO FY-3: 6-frequency, 12-channel MW radiometer, (10.7–150 GHz, V/H)	2015	Precipitation Temperature/humidity sounding Cloud liquid and ice water	First MW imager on GEO
GOES-R (NOAA/NASA) *USA*	(1) Advanced Baseline Imager (ABI) (2) Space Environmental In-Situ Suite (SEISS) (3) Solar Ultra Violet Imager (SUVI) (4) Extreme Ultra Violet/X-Ray Irradiance Sensors (EXIS) (5) Geostationary Lightning Mapper (GLM) (6) Magnetometer (MAG)	(1) 16-channel multispectral VIS-IR imager (0.45–13.6 μm); $x = 0.5–2$ km (2) 11-channel instrument with magnetospheric (MPS), energetic heavy ion (EHIS), solar/galactic proton sensor (SGPS) (30 eV to 4 MeV; 30 eV to 500 MeV; > 500 MeV) (3) 6-channel imager, (0.9–32 nm) (4) 3.channel irradiance Sensor (5–127 nm) (5) 0.7774 μm oxygen emission channel; $x = 10$ km (6) ±1000 nT with 0.016 nT	2015	Aerosol optical depth (1) Cloud properties (1) Radiation components (1) Rainfall rate (1) Columnar water vapour (1) Temperature and moisture profiles (1) Motion winds (1) LST/SST (skin) (1) Snow cover (1) Energetic heavy ions (2) Magnetic electrons and protons (2) Solar and galactic protons (2) Solar imagery: X-Ray (3) Solar flux: EUV, Flux: X-ray (4) Lightning events (5) Geomagnetic field (6)	Improved resolution (4X), faster coverage (5 X), more bands (3 X), better imagers VIS inflight calibration Continuous coverage of total lightning flash rate over land and water Additional solar/space monitoring Improved heavy ion detection, adds low energy electrons and protons
HIMAWARI-8 (JMA) *Japan*	(1) Advanced Baseline Imager (ABI)	→GOES-R	2014	→GOES-R	→GOES-R
INSAT-3D (IMA/ISRO) *India*	(1) Imager (INSAT) (2) Sounder (INSAT)	(1) 6-channel VIS/IR radiometer (0.65–12 μm), $x = 1–8$ km (2) 19-channel IR radiometer + 1 VIS (3.7–14.7 μm), $x = 10$ km	2011	Cloud properties (1) Cloud and WV motion winds (1) Radiation components (1) Rainfall rate (1) Temperature/humidity profiles (2)	
Meteosat Third Generation (MTG) (ESA/EUMETSAT) *Europe*	(1) Flexible Combined Imager (FCI) (2) Lightning Imager (LI) (3) InfraRed Sounder (IRS) (4) Ultra Violet and Near Infrared Sounder (UVN)	(1) 18-channel VIS/IR radiometer, $x = 0.5–2$ km (2) Narrow band (1.4 nm) imager (777.4 nm); $x = 10$ km (3) 10-channel Michelson Fourier Transform Spectrometer; $x = 3–6$ km; $z = 1–2$ km (4) High-resolution spectrometer (UV:290–400 nm; VIS:400–500 nm; NIR:755–775 nm); $x = 10$ km	2017	Loud properties (1) Full disc lightning discharges (2) WV 3-D wind vectors (3) 3-D temperature/humidity fields (3) Pollution cloud and plume detection (O_3, NO_2, SO_2 und H_2CO) (4) Aerosol profile (4) UV radiation (4)	Improved MSG-SEVIRI/HRV Very-short-term nowcasting of cloud development Continuously full disc lightning discharges Higher resolution profiles Clear-sky wind fields First time air quality surveillance on GEO

[a] Tentative launch data, x, nominal horizontal resolution.

climate research, but also the implementation of new operational products. Most LEO programmes have been recently updated, such as, e.g., the FY-3 mission of CMA (Zhang *et al*., 2006) and the Russian Meteor-M-N1 (http://planet.iitp.ru/english/index_eng.htm; accessed 24 March 2011).

The next updates of operational LEO systems to next generation status are expected for the European and the US-American programmes (see Table II). For the latter, the second generation LEO mission Joint Polar Satellite System (JPSS) will follow the NOAA series after 19 satellites are launched. The payload will take advantage of current experimental in-orbit LEO missions such as EOS-Terra and Aqua. The multi-purpose imager represents a subset of the successful MODIS sensor onboard Terra/Aqua going into operational uses (Schueler and Barnes, 1998). It has the high potential to observe cloud and retrieve their properties with higher accuracy (Hutchison *et al*., 2005; Wong *et al*., 2007). This is also the case for land surface parameters related to climate, as vegetation index, snow and fires (Townshend and Justice, 2002) as well as land (LST) and sea (SST) surface temperatures (Yu *et al*., 2005). The sensor is also designed to trace aerosols and smoke plumes where a novel feature will be the analysis of clouds and land surfaces under very low light conditions which will help to improve cloud products, for example, (Lee *et al*., 2006). The key instrument to construct vertical profiles of atmospheric temperature and moisture is an interferometric sounding sensor, the Cross-track Infrared Sounder

Table II. Major approved and planned next generation LEO missions.

Mission (agency), *orbit*	Sensor	Technology	Launch[a]	Priority products	Improvement
Joint Polar Satellite System (JPSS) (NOAA/NASA) *USA*	(1) Visible/Infrared Imager/Radiometer Suite (VIIRS) (2) Cross-track Infrared Sounder (CrIS) (3) Advanced Technology Microwave Sounder (ATMS) (4) Ozone Mapping and Profiler Suite (OMPS) (5) Clouds and the Earth's Radiant Energy System (CERES)	(1) 22-channel VIS-IR radiometer (0.3–14 μm), $x = 0.4$ km (2) Scanning Fourier Transform IR Spectrometer (3.9–15.4 μm); $x = 14$ km (3) 22-channel MW radiometer (23–183 GHz), $x = 16–75$ km (4) Nadir total column spectrometer (300–380 nm) and nadir profile spectrometer (250–310 nm, $x = 50–250$ km; $z = 5$ km (up to 60 km) (5) 3-channel broadband imager (0.3 > 50 μm), $x = 10–20$ km	2014	Cloud properties (1–3) SST/LST (1, 2) Precipitation type/rate (1–3) Atmospheric temperature, moisture and pressure profiles and columnar values (2, 3) Soil moisture (3) Vertical/horizontal ozone distribution (4) Components radiation balance (5)	Continuation and improvement of LEO missions on e.g. TERRA, AQUA, DMSP etc. Day/night band for low levels of VIS-NIR radiance Higher (spatial, temporal, and spectral) resolution Higher radiometric calibration and accuracy More accurate soundings NWP assimilation quality
Post-EPS (ESA/EUMETSAT) (Feasibility study pending) *Europe*	(1) Visible/Infrared Imaging (VII) (2) Low Light Imaging (LLI) (3) Infrared Sounding (IRS) (4) Microwave Sounding (MWS) (5) Radio Occultation (RO) (6) Nadir viewing UV/VIS/NIR - SWIR Sounding (UVNS) (7) Multi-viewing, -channel, -polarization Imaging (3MI) (8) Scatterometry (SCA) (9) Microwave Imaging (MWI) (10) Radiant Energy Radiometry (RER)	(1) 16-channel multispectral imager (0.44–13.4 μm) (2) OLS-like; radiometer(0.47–0.95 μm photo-multiplier tube) (3) IASI-heritage (4) ATMS-like → JPSS (5) Limb scanning, $z = 0.5$ km (6) GOME-2, SCIAMACHY, OMI heritage → to be specified (7) Polder-like, nine-wavelength radiometer with three polarizations at four wavelengths (0.44–0.9 μm; 20 nm width); $x = 4$ km (8) ASCAT-like, side looking C-band radar scatterometer (5.255 GHz); $x = 25$ km (9) MW radiometer AMSR-E heritage (18.7–664 GHz) (10) CERES-like → JPSS	2020	Cloud properties (1, 7,8) Aerosol properties (1, 2, 6, 7) LST/SST, surface albedo (1, 3, 7) Snow cover (1, 2) Land surface (Vegetation, fire) (1) Ocean colour (1,7) Night-time cloud imagery (2) Temperature/humidity profile and humidity columns (3, 4, 5, 8) Trace gases (3, 6) Cloud liquid water total column (4) Bending angles profiles (5) Ionospheric electron content (5) Ozone profile and column (6) Ocean surface wind vectors (8) Soil moisture (8) Snow equivalent water (8) Sea-ice properties (8, 9) Precipitation (9) Radiation balance components	High vertical resolution sounders High spatial resolution Temperature/humidity profile also under cloud contamination More than 4000 occultation *per* day by tracking GPS and Galileo Focus on air quality monitoring High frequency MW for cloud products

[a] Tentative lauch data, x, nominal horizontal resolution.

(CrIS) (Bloom, 2001) in combination with the Advanced Technology Microwave Sounder (ATMS) (Muth *et al.*, 2004). Kleespies (2007) stressed that ATMS can significantly improve temperature and moisture retrievals in comparison to current in-orbit sounder technology only if footprint matching is employed to use oversampled ATMS observations. Advanced retrieval of ozone will be warranted by the novel ozone mapping and profiler suite (OMPS, Flynn *et al.*, 2004) in conjunction with the development of new algorithms particularly addressing the greater spectral coverage and better height resolution of the suite (Flynn *et al.*, 2009).

The follow-on mission of the successful European Meteorological Operational (MetOp) platform is still in the planning stage which means that most instruments are not yet specified. The Post-EPS feasibility study starts in 2011 and concentrates on several missions which are mostly developments of successful missions currently onboard experimental LEO missions. The core instrument will be a MODIS-like high-performance multispectral imaging radiometer, the Visible-Infrared Imager (VII) (Schmülling *et al.*, 2010). Low light imaging is also an important topic where a sensor will be most likely adapted from NOAA OLS (Operational Linescan System on DMSP; e.g. Elvidge *et al.*, 1998; Cinzano *et al.*, 2000). A higher accuracy and vertical resolution will be achieved with Radio Occultation (RO) by improving the GRAS sensor currently flying on MetOp (Loiselet *et al.*, 2000). One major focus of Post-EPS is to bring hitherto experimental atmospheric chemistry missions onto an operational LEO platform. The Nadir viewing UV/VIS/NIR – SWIR Sounding (UVNS) unit will be a development of successful SCIAMACHY and OMI instruments and is mainly dedicated to trace gas cartography of the atmosphere (Schlüssel *et al.*, 2009). This is also supported by the Multi-viewing, channel and polarization imaging (3MI sensor), an instrument similar to the POLDER instrument (Polarization and Directionality of the Earth Reflectances) (Deschamps *et al.*, 1994; King *et al.*, 1999). A further instrument transferred to operational application will be a device derived from the active C-band scatterometer ASCAT, mainly for the retrieval of Ocean surface wind vectors (Figa-Saldaña *et al.*, 2002). To improve quantitative precipitation (Nielsen and Long, 2009) and soil moisture (Njoku *et al.*, 2003) retrievals, as well as cloud and snow liquid water estimates, a microwave radiometer mission is proposed which will be based on the AMSR-E instrument on board EOS-Aqua (Parkinson, 2003).

2.2.3. *Approved near future experimental missions*

While the future operational GEO and LEO systems mostly rely on passive instruments, experimental missions will be used particularly to develop active RADAR and LIDAR sensors (Table III). The major aims of the upcoming experimental LEO missions are to improve atmospheric sounding of temperature and humidity, but major attention is given to novel technologies to retrieve rainfall and cloud properties and their vertical distribution. Some of the missions only relying on passive instruments are partly compatible to the next generation operational LEO missions. The Japanese Space Agency plans to launch two polar platforms of the Global Change Observation Mission (GCOM), where the first satellite GCOM-C will carry a second generation imager while the second (GCOM-W) will be equipped with an Advanced Scanning Microwave Radiometer (Sasaki and Nakagawa, 2009). The MODIS-like Second-Generation Global Imager (SGLI) which offers 19 spectral channels has a special feature, the three polarization angle (0, 60 and 120°) polarimeter. Polarization observations in the range of 670 and 865 nm with tilting function will particularly be used to improve the retrieval of aerosol properties over land surfaces (Okamura *et al*., 2008; Tanaka *et al*., 2009). The Advanced Microwave Scanning Radiometer-2 (AMSR2) will be installed on GCOM-W. A major advantage of AMSR2 is its large revolving space antenna (2 m) and the ability to detect very weak MW signals at an increased temporal resolution which will improve the retrieval quality of precipitation and atmospheric humidity. An additional 7.3 GHz channels will mitigate radio-frequency interferences (Kachi *et al*., 2008). The stratospheric wind interferometer for transport studies (SWIFT) will not only measure stratospheric winds but also ozone densities by means of the wind-induced phase shifts of interferograms from atmospheric limb radiance spectra in the vicinity of the vibration–rotation ozone line at 8.82 μm (Shepherd *et al*., 2001; Rahnama *et al*., 2006). A new satellite of the ESA's Earth Explorer core missions, ADM-Aeolus (Atmospheric Dynamics Mission) will measure vertical wind profiles from space. The mission employs a high-performance Doppler wind lidar based on direct-detection interferometric techniques (refer to Stoffelen *et al*., 2005). Tan and Andersson (2005) showed that, based on simulations, the gained accuracy for both, the boundary layer and the free troposphere is sufficient for global data-assimilation systems. As a development of recent satellites and instruments such as Cryosat, MERIS and the improved AATSR (both on Envisat), the European Sentinel-3 mission will observe a wide range of land, ocean and atmospheric parameter in the frame of the Global Monitoring for Environment and Security (GMES) program of ESA. The core instrument of the topography mission is the SRAL radar altimeter (Le Roy *et al*., 2010). The two-channel microwave radiometer (MWR) aims at the analysis of ice and snow (Tran *et al*., 2008). The Ocean Land Color Instrument (OLCI) is planned as an improved successor to MERIS while the Sea and Land Surface Temperature Radiometer (SLSTR) provides data continuity from the previous AATSR and ATSR-1/2 instruments. Two more SWIR channels will support better clouds and aerosols screening while two further channels are added for global-scale fire monitoring (Coppo *et al*., 2010). Three future missions are especially devoted to rainfall, cloud and aerosol remote sensing. The first French/Indian mission, Megha-Tropiques, relies on passive instruments and is restricted to the tropics (from 23 °N to 23 °S) due to its inclined orbit which, however, provides high temporal resolution, inevitably to study tropical convection with short life cycles (Karouche and Raju, 2010). The core instrument for rainfall retrievals, the MADRAS MW imager, will be a development of the TRMM-TMI sensor. Compared to TMI, higher MADRAS frequency channels at 89 and 157 GHz might help to improve the retrieval of ice phase hydrometeors (Balaji *et al*., 2009). The humidity sounder SAPHIR is designed to provide the humidity profile (Eymard *et al*., 2001). This satellite will also carry an ERB (Earth Radiation Budget) instrument called the Scanner for Radiation Budget (ScaRaB) which has been proven to deliver somewhat lower data quality than the ERB CERES (JPSS) mission (Viollier *et al*., 2009). The second future mission dedicated to rainfall retrieval is the core satellite of the Global Precipitation Measurement (GPM) mission (for GPM refer to Smith *et al*., 2007). The satellite is a direct development of the TRMM mission with its first precipitation radar in space. Consequently, the GPM core harbours a passive microwave imager (GMI) and dual-frequency precipitation radar (DPR) (Flaming, 2005). GMI is similar to TRMM's TMI but will provide significantly improved spatial resolution thanks to a bigger 1.2 m diameter antenna (Bidwell, 2005). The dual-frequency of the precipitation radar (DPR) is a great step forward in comparison to the single-frequency PR on TRMM. This shall allow the retrieval of more accurate rain rates in areas of cold clouds which are frequently characterized by solid precipitation with deviating hydrometeor shapes (Nakamura *et al*., 2005). The mission devoted to aerosol, clouds and rainfall is one of ESA's future Earth Explorer core missions Earth-Care with its four instruments: an atmospheric backscatter lidar, a cloud profiling radar, a multi-spectral imager and a broad band radiometer (Bezy *et al*., 2005). A general improvement compared to the Cloudsat mission's radar is the Doppler capability of EarthCare's CPR. However, Schutgens (2008) showed with simulations that the large forward motion of the Doppler cloud profiling radar might cause biases in the observed Doppler speeds which have to be corrected by respective algorithms. The synergy between the lidar and the cloud radar, especially, is suggested to improve the retrieval of radiative and microphysical properties of clouds (Tinel *et al*., 2005).

Table III. Approved experimental missions.

Mission (agency), *orbit*	Sensor	Technology	Launch[a]	Priority products	Improvement
ADM-Aeolus (ESA) *LEO*	(1) ALADIN (Atmospheric laser Doppler instrument)	(1) Doppler Wind Lidar (355 nm), $x = 50$ km, $z = 0.5–2.5$ km	2013	Vertical wind profiles (0–30 km) Vertical profiles of cloud properties Aerosol optical depth and distribution	Improved analysis of circulation systems Provides for the first time global wind profiles Wind parameters meet NWP assimilation accuracy requirements
Chinook (CSA) *LEO*	(1) SWIFT (Stratospheric Wind Interferometer for Transport Studies) (2) ARGO (Atmospheric Research with GPS Occultation)	(1) Doppler IR radiometer (at 9 µm), $x = 15–55$ km, $z = 3–5$ km (2) IGOR (Integrated GPS Occultation Receiver); $x = 8–160$ km; $z = 0.5$ km	2011	Ozone concentration (1) Stratospheric wind (1) Bending angle (temperature, humidity) (2)	Improved accuracy First time global observation of stratospheric winds Assimilation to NWP
EarthCARE (ESA/JAXA) *LEO*	(1) HSR (High Spectral resolution lidar) (2) CPR (Cloud Profiling Radar) (3) MSI (Multi-Spectral Imager) (4) BBR (Broadband Radiometer)	(1) Lidar (355 nm), $z = 100–300$ m, $x = 0.1–10$ km (2) Doppler millimeter wave radar (94 GHz), $z = 500$ m, $x = 1–10$ km (3) Multi-spectral imager (seven bands, 0.6.12 µm), $x = 1$ km (4) Two band (broadband SW and LW), $x = 10$ km	2015	Vertical profiles aerosol extinction Aerosol type Vertical profiles clouds properties Mass flux in clouds Drizzle and precipitation rates Vertical radiative flux gradients	First space-borne radar with a Doppler capability Higher accuracy Parameters meet NWP assimilation accuracy requirements
Global Change Observation Mission (GCOM), GCOM-C (Climate) (JAXA) *LEO*	(1) Second-generation Global Imager (SGLI)	(1) 19-channel radiometer (0.38–12 µm), $x = 0.25–1$ km	2014	Cloud properties Aerosol properties Ocean colour Vegetation index	Improves MODIS Polarimetry function Forward/backward function in red/NIR
Global Change Observation Mission (GCOM), GCOM-W (Water) (JAXA) *LEO*	(1) Advanced Microwave Scanning Radiometer-2 (AMSR2)	(1) MW radiometer with six frequencies/12 channels (V/H) (6.9–89 GHz); x = 5–10 km	2012	Precipitation Atmospheric moisture Soil moisture, snow depth SST Sea surface wind speed	Largest revolving space antenna Detects weak MW signals Higher accuracy High temporal resolution due to revolving antenna
Global Precipitation Measurement (GPM) mission core satellite (NASA/JAXA) *LEO, non-sun synchronous orbit*	(1) GPM Microwave Imager (GMI) (2) Dual–frequency Precipitation Radar (DPR)	(1) 13-channels (10–183 GHz), $x = 4.4–32.2$ km (2) Ku-band (13.6 GHz) and Ka-band (35.6 GHz) precipitation radar; $x = 5$ km	2013	3-D cloud structure 3-D rainfall and rain rates	Improves TRMM-TMI by four high frequency channels about 166 and 183 GHz Improvement of TRMM-PR by adding Ka-band radar High temporal resolution; 3 h global rain maps Higher sensitivity for light rain and solid precipitation detection
Megha-Tropiques (CNES, ISRO) *LEO, 20° inclination above the equator*	(1) Microwave Analysis and Detection of Rain and Atmospheric Structures (MADRAS) (2) Humidity Sounder (SAPHIR) (3) Scanner for Radiation Budget Measurement (SCARAB)	(1) Self-calibrating microwave imager, 5-channels (18.7–157 GHz), H + V polarization; $x = 6–40$ km (2) 6-channel passive microwave humidity sounder (183.31 ± 12 GHz); $x = 10$ km (3) Multi-spectral scanning radiometer, 4-channel (0.5–12.5 µm); $x = 40$ km	2011	Cloud condensed water content Cloud ice content Convective-stratiform cloud discrimination Rain rate Latent heat release Integrated water vapour content Radiative fluxes at the top of the atmos-phere Sea surface wind	High temporal sampling of a MW system Can follow the life cycle of tropical mesoscale convective systems
National Polar-orbiting Operational Environmental Satellite System (NPOESS) (NOAA/NASA) *LEO*	(1) Visible/Infrared Imager/Radiometer Suite (VIIRS) (2) Cross-track Infrared Sounder (CrIS) (3) Advanced Technology Microwave Sounder (ATMS) (4) Microwave Imager/Sounder (MIS) (5) Ozone Mapping and Profiler Suite (OMPS) (6) Clouds and the Earth's Radiant Energy System (CERES) (7) Space Environment Monitor (SEM-N)	(1) 22-channel VIS-IR radiometer (0.3–14 µm), $x = 0.4$ km (2) Scanning Fourier Transform IR Spectrometer (3.9–15.4 µm); $x = 14$ km (3) 22-channel MW radiometer (23–183 GHz), $x = 16–75$ km (4) 10-channel instrument (6–183 GHz; 4 VH polarized; 3 polarimetric), $x = 10$-40 km (5) Nadir total column spectrometer (300–380 nm) and nadir profile spectrometer (250–310 nm, $x = 50–250$ km; $z = 5$ km (up to 60 km) (6) 3-channel broadband imager (0.3–50 µm), $x = 10–20$ km (7) Special Sensor J5 (SSJ5) for low-energy, Energetic Particle Spectrometer (EPS) for medium-energy, and omnidirectional detectors for high-energy particles	2013	Cloud properties (1–4) SST/LST (1,2) Precipitation type/rate (1–4) Atmospheric temperature, moisture and pressure profiles and columnar values (2, 3, 4) Soil moisture (3, 4) Vertical/horizontal ozone distribution (5) Components radiation balance (6) Space weather (7)	Continuation and improvement of LEO missions on e.g. TERRA, AQUA, DMSP etc. Day/night band for low levels of VIS-NIR radiance Higher (spatial, temporal, and spectral) resolution Higher radiometric calibration and accuracy More accurate soundings NWP assimilation quality
Sentinel-3 (EUMETSAT) *LEO*	(1) Synthetic Aperture Radar Altimeter (SRAL) (2) Microwave radiometer (MWR) (3) Ocean Land Color Instrument (OLCI) (4) Land Surface Temperature Radiometer (SLSTR)	(1) Dual-band Ku- (13.575 GHz) and C-band (5.41 GHz), $x = 0.3$ km (2) Two-channel microwave radiometer (23.8, 36.5 GHz), $x = 20$ km (3) Medium Resolution Imaging Spectrometer, 21-channels UV to NIR; $x = 0.3–1.2$ km (4) Dual viewing technique, 9-channels (0.555–12 µm), $x = 0.5–1$ km	2013	Ocean, ice, land and inland water surface topography (1) Integrated atmospheric water vapour column (2) Cloud liquid water content (2) Ocean colour (3) Land surface biophysical properties (3) LST/SST (4)	Improvement Cryosat With atmospheric correction Improved MERIS Reduced sunglint effect Improved AATSR

[a] Tentative year of launch; x, nominal horizontal resolution, z, nominal vertical resolution; ESA, European; CSA, Canadian; JAXA, Japanese; NASA, American; CNES, French; and ISRO, Indian Space Agencies. LEO, Low Earth Orbit; GEO, Geostationary Earth Orbit.

3. Meteorological parameters

After the overview of past, current and future satellite systems, the following section focuses on the respective meteorological parameters most relevant for a better understanding of the Earth-atmosphere system (see also Table S2).

3.1. Radiation

Radiation energy and its spatio-temporal distribution is the driver for atmospheric dynamics. To understand weather and climate, measurements of the radiation that enters and leaves the Earth-atmosphere system are necessary. To provide these measurements, a succession of satellite instruments have been developed (Table S2). Satellite-based methods for estimating the long wave radiation balance are reviewed in Schmetz (1989). More recently, Loeb *et al*. (2007) summarized observed radiation retrievals from different sensors.

The Earth's radiation budget (ERB) operational product at NOAA/NESDIS has a history since 1974. The ERB consists of two components: the emitted long wave radiation at the top of the atmosphere (TOA) (OLR: outgoing long wave radiation), and the absorbed solar radiation, (ASR: absorbed solar radiation or net solar radiation). The algorithm was developed for the NOAA AVHRR series. Its development and continuous improvements are documented in Wydick *et al*. (1987), Ruff and Gruber (1988) and Taylor (1990).

The ERBE instruments provided radiation flux information at the top of the atmosphere (TOA) since 1984 (Barkstrom and Smith, 1986; Barkstrom *et al*., 1989). Ellingson *et al*. (1989) developed a multispectral regression technique to estimate OLR using the HIRS radiance observations. This algorithm was further adapted for the Geostationary Operational Environmental Sounder (GOES) (Ba *et al*., 2003), as well as for the GOES Imager (Lee *et al*., 2004). ERBE data provided insights in the great importance of clouds in regulating the radiation budget (Ramanathan *et al*., 1989; Harrison *et al*., 1990). As a result, the Clouds and Earth Radiant Energy System (CERES) sensor was designed to provide radiation fluxes at the surface and at levels throughout the atmosphere and to investigate the cloud-radiation feedback on the Earth's climate system (Wielicki *et al*., 1996; Loeb *et al*., 2001; Geier *et al*., 2003). Huang *et al*. (2008) and Sun *et al*. (2010) used collocated AIRS hyperspectral radiance measurements and CERES outgoing long wave fluxes to estimate TOA OLR from AIRS radiance measurements.

3.2. Surface temperature

Retrievals of the sea surface temperature (SST) and land surface temperature (LST) from space provide information for interactions between ocean/land and atmosphere such as evaporation processes and boundary layer dynamics.

Satellite measurements of SST have been provided by the NOAA/AVHRR with multiple infrared channels since 1981 (McClain *et al*., 1983, Table S2). SST and LST retrievals using IR channels are based on the fundamental theory, that differential spectral absorption in multiple infrared channels is used to obtain absolute SST estimates (McMillin and Crosby, 1984; McClain *et al*., 1985). This so-called 'split-window' method is being used successfully to retrieve the sea surface temperature from satellite radiances where the emissivity is assumed equal to unity (Njoku *et al*., 1985). It relies on the fact that the atmospheric attenuation is greater in the 12.0 μm channel than in the 11.0 μm channel. As the attenuation increases, primarily as a result of increasing atmospheric water vapour, the difference in the radiance measured in the two bands increases. Since the surface source of the radiance does not change between the bands, the differential shift in sensor measured radiance originates from atmospheric attenuation (Ouaidrari *et al*., 2002).

The split window method has been modified to retrieve land surface temperature and several split-window equations have been developed for the land surface (e.g., McClain *et al*., 1985; Prata, 1994a, 1994b; Sobrino *et al*., 1996). Modified versions of the split window algorithms have been successfully applied to the LST retrieval from the data observed by MODIS and SEVIRI (Sobrino and Romaguera, 2004; Wan *et al*., 2004; Trigo *et al*., 2008).

Infrared measurements of SST can only be obtained in cloud free conditions. Furthermore, IR estimates of SST are also contaminated by high atmospheric aerosol loading (Diaz *et al*., 2001). Because clouds and aerosols are essentially transparent to microwave radiation at frequencies below about 12 GHz, microwave remote sensing has the potential to eliminate the atmospheric contamination. Microwave estimates of SST are possible because the surface radiance is proportional to SST at frequencies between about 4 and 12 GHz. However, SST retrievals at these frequencies must consider the effects of wind on the emissivity of the sea surface (Chelton and Wentz, 2005). High-quality microwave SST data first became available from measurements at 10.7 GHz by the TRMM TMI (Wentz *et al*., 2000). With its cloud-penetrating ability, AMSR-E provides a unique dataset of global all-weather SST measurements (Chelton and Wentz, 2005). AMSR-E retrievals of SST are based on measurements of brightness temperature at 6.9 GHz, which is more sensitive to SST than are the 10.7-GHz measurements used in TMI retrievals. The empirical retrieval algorithm for SSM/I matches the SSM/I brightness temperature with buoy and/or radiosonde measurements by means of a neural network algorithm (Stogryn *et al*., 1994; Krasnopolsky *et al*., 1995; Liu *et al*., 2001).

LST exhibits a strong diurnal variability that cannot be captured from polar orbiting satellites that sample each location approximately twice a day. Geostationary satellites provide diurnal coverage, and allow derivation of the LST diurnal cycle.

3.3. Wind

Wind fields derived from satellites provide continuous area-wide information about atmospheric dynamics in a high spatial and temporal resolution. Such information is of great benefit as an input parameter for numerical weather prediction. Thus, atmospheric motion vectors, derived by tracking atmospheric features (e.g. clouds or water vapour) with satellites were one of the first satellite data products assimilated in global numerical weather prediction (Hayden *et al*., 1993; Eyre, 1997; Tomassini *et al*., 1999; Menzel, 2001).

Satellite-based winds are derived from a variety of active and passive techniques (see Table S2). A comprehensive review is given in Isaacs *et al*. (1986) and Kidder and Vonder Haar (1995).

Winds at higher atmospheric levels are deduced by tracking the motion of features in satellite imagery. The tracking technique relies on passive optical satellite data, preferably from geostationary systems (Fujita, 1968; Hubert and Whitney, 1971). This technique estimates the horizontal wind by determining the vector difference of the location of a feature in successive images. The method is applicable in any spectral region in which distinctive features may be identified. Most popular are the visible and infrared channels where clouds act as tracers to be tracked (Allison *et al*., 1972; Fischer *et al*., 1981; Le Marshall *et al*., 1985; Stewart *et al*., 1985). The retrieved winds are called cloud motion vectors (CMV). Other channels are the 6.7 μm water vapour band (Laurent, 1993; Velden *et al*., 1997) or the 15 μm CO_2 band (Menzel *et al*., 1983), for which the retrieved winds are called atmospheric motion vectors (AMV).

Nowadays, satellite-based winds are retrieved from all operational geostationary satellites. For polar latitudes, Key *et al*. (2002) retrieved CMV/AMV from MODIS data, which provide a temporal resolution of about 1 h in the Polar Regions. Horvath and Davies (2001a, 2001b) and Moroney *et al*. (2002) presented a retrieval of CMV for the Multiangle Imaging SpectroRadiometer (MISR) on the Terra satellite. These are derived by matching cloud reflectivity patterns from three different view angles. The across-track and along-track disparities are considered to determine height of cloud tops and the motion effects separately. The results are the cloud motion components parallel to and orthogonal to the satellite's direction.

Wind fields near the surface can be determined from the observed microwave emissivity of the ocean surface (e.g., Wilheit and Chang, 1980; Meissner *et al*., 2001). In constructing algorithms to retrieve ocean wind speed from passive microwave radiometers, higher frequencies (such as 36 GHz) rather than lower frequencies are commonly used to retrieve low to moderate winds up to 25 m s^{-1} in no-rain areas, since the sensitivity to ocean wind at higher frequencies is better than that at lower frequencies (Wentz, 1983). Kidder *et al*. (1978, 1980) developed a statistical method for the 55.45 GHz channel of the Scanning Microwave Spectrometer on Nimbus-6 to study for the first time surface wind speed in tropical cyclones. This was followed by algorithms developed by Velden and Smith (1983), Velden (1989) and Velden *et al*. (1991) who expanded the use of high-resolution data from the Microwave Sounding Unit (MSU) on National Oceanic and Atmospheric Administration (NOAA) polar-orbiting satellites. Brueske and Velden (2003) extended the work of Kidder *et al*. (1978) to estimate wind speed in tropical cyclones from AMSU data, a successor of the MSU.

WindSat is the first passive microwave polarimetric radiometer. The objective of WindSat is to demonstrate the capability of polarimetric, microwave radiometers to measure near-surface ocean wind speed and direction in all-weather conditions (Connor *et al*., 2004; Gaiser *et al*., 2004). The WindSat wind retrieval algorithm uses a variational technique in which the atmospheric state vector is found, which minimizes the difference between the satellite radiance measurements and the forward-model equivalents (Bettenhausen *et al*., 2006). Kim and Lyzenga (2008) proposed a method for estimating the atmospheric transmittance and wind speed over the ocean from WindSat data. They used a simplified model for the ocean surface reflectivity to calculate both the surface emissivity and the reflection of downwelling atmospheric radiation.

Near-surface winds over oceans can also be derived from microwave radar backscatter from the ocean (e.g., Cardone *et al*., 1983; Chelton and Freilich, 2005). The backscattering co-efficient is mainly influenced by the wind speed and the angle formed by the wind vector and the satellite's antenna direction. Wind speed and direction can be deduced from a set of near-simultaneous measurements of backscatter co-efficient at a single location for different viewing angles. Therefore, scatterometer sensors have several antennae, or a rotating antenna and two radar beams in the case of the SeaWinds sensor (Fichaux *et al*., 2005). The use of radar scatterometers to measure the ocean surface wind vectors is well established (Moore and Jones, 2004). Scatterometers such as the Active Microwave Instrument (AMI) on the European Remote Sensing (ERS) 1 and 2 satellites have observed global ocean winds continuously since the early 1990s (Fichaux *et al*., 2005; Adams *et al*., 2006). The utility of QuikSCAT winds in the analysis and forecasting of extra tropical cyclones and marine weather in the mid- and high latitudes is documented by Atlas *et al*. (2001), Chelton *et al*. (2006) and Von Ahn *et al*. (2006).

SeaWinds scatterometer data have been used for tropical cyclone forecasting (Jones *et al*., 1999; Weissman *et al*., 2003). The Advanced SCATterometer (ASCAT) aboard MetOp was launched by EUMETSAT to measure surface wind (Figa-Saldaña *et al*., 2002).

Synthetic Aperture Radar (SAR) combines the measurement of a backscattering coefficient with the azimuth Doppler analysis of the measured signal. This enables measurement of backscattering coefficients with a high spatial resolution (Fichaux *et al*., 2005).

3.4. Water vapour

Water vapour is the principal greenhouse gas in the atmosphere and a key compound of the global climate (Gedzelman *et al.*, 2003). It is important for many atmospheric processes, such as radiative transfer, circulation dynamics (Hanisco *et al.*, 2007; Strong *et al.*, 2007), cloud formation (Schmidt *et al.*, 2005), precipitation (Bowen and Revenaugh, 2003) and the greenhouse effect (Schneider *et al.*, 2006; Hartmann, 2002). Information about the distribution and variability of atmospheric water vapour is critical for understanding these processes controlling the Earth radiative budget and the hydrological cycle.

Several efforts have been made to use satellite datasets to measure the spatio temporal distribution and variability of atmospheric water vapour (see Table S2). A good overview and summary can be found in Kley and Russel (2001). Passive methods for retrieving water vapour (or precipitable water vapour, the vertical integral of the water vapour mixing ratio) exploit water vapour absorption bands in three distinct spectral domains. Methods based on solar reflectance channels rely on absorption between about 0.9 and 1.0 µm (Gao and Kaufman, 2003; Albert *et al.*, 2005). Methods based on thermal-infrared channels rely on absorption and emission between about 6.5, 8.7 and 12 µm (Seemann *et al.*, 2003). Microwave techniques exploit water vapour absorption lines at either 22.2 or 183.3 GHz (Engelen and Stephens, 1999; Sohn and Smith, 2003).

Several studies showed that measurements in the visible spectral region can be used to derive water vapour total columns (e.g. Noel *et al.*, 1999; Casadio *et al.*, 2000; Maurellis *et al.*, 2000; Lang *et al.*, 2003; Wagner *et al.*, 2003; Buchwitz *et al.*, 2004). One of these retrieval methods is the so-called Air Mass Corrected Differential Optical Absorption Spectroscopy approach (e.g. Noel *et al.*, 1999, 2004, 2005, 2008) which also relies on water vapour and molecular oxygen absorption between 688 and 700 nm to derive total column water vapour.

MODIS provides five near-infrared bands located within and around the 0.94 µm water vapour band, that are used to retrieve column water vapour amounts (King *et al.*, 2003). The retrieval relies on observations of water vapour absorption of near-infrared solar radiation reflected by the bottom surface and uses ratios of water vapour absorbing bands (within the 0.94 µm water vapour band) with atmospheric window bands at 0.86 and 1.24 µm to derive atmospheric water vapour transmittances (King *et al.*, 1992). Bennartz and Fischer (2001) describe an algorithm to derive columnar water vapour from backscattered solar radiation in the MERIS near-infrared channels using radiative transfer simulations for the MERIS 900 and 885 nm channels.

The water vapour absorption band at 6–7 µm of NOAA/TOVS and its successor NOAA/ATOVS is used to retrieve water vapour in the atmosphere (Chaboureau *et al.*, 1998 and references therein). Soden and Bretherton (1994) and Jackson and Bates (2001) used the GOES 6.7 µm channel to estimate atmospheric water vapour. The NESDIS/CIMSS three-layer precipitable water product integrates GOES sounding retrievals to provide a measurement of the layer and total precipitable water in clear and partly cloudy conditions (Schmit *et al.*, 2002).

Several techniques for estimating precipitable water vapour use data from two adjacent channels in the infrared split-window region near 10–12 µm (GOES, Birkenheuer and Gutman, 2005).

Milz *et al.* (2005) present water vapour profiles obtained from infrared limb emission measurements recorded by the Michelson Interferometer for Passive Atmospheric Sounding (MIPAS) on ENVISAT. The retrieval is based on constrained non-linear least squares fitting.

Typical sensors for water vapour retrieval methods based on microwave wavelength radiances are MSU/AMSU (Staelin *et al.*, 1976), SSM/I or the SSM Temperature and Water vapour Profiler (SSM/T) (Schlüssel and Emery, 1990; Bauer and Schluessel, 1993). Grody *et al.* (1998) used radiative transfer simulations to derive total precipitable water vapour from AMSU dual-frequency microwave channels. The optimal channel combination and coefficients were obtained by performing regression analysis on the simulated AMSU measurements and standard sounding as well as surface data. Houshangpour *et al.* (2005) developed a regression method to retrieve upper tropospheric water vapour from AMSU radiances. Singh and Bhatia (2008) propose a neural-network-algorithm using simulated brightness temperatures at four frequencies, 23.4, 31.4, 50.3 and 89.0 GHz for the retrieval of precipitable water vapour from AMSU data. The method is based on surface observations of the skin temperature and ocean surface, wind speed and direction. Deeter (2007) presents a method for retrieving precipitable water vapour using observations from AMSR-E. The method relies on a simple but accurate parameterization which relates AMSR-E polarization-difference signals at 18.7 and 23.8 GHz to precipitable water vapour, liquid water path and the surface emissivity polarization difference.

3.5. Gases

As a response on the increasing human impact on the evolution of the global climate and on the stratospheric ozone layer much effort has been made to understand the underlying chemical and physical processes and the role of anthropogenic gas emissions. To fulfill this objective there is a clear need for global observation of gas emissions and concentrations in the Earth atmosphere system (Nett *et al.*, 2001). Satellite measurements are a powerful tool for monitoring gas emissions, since the whole globe is observed with a single instrument over long periods (Beirle *et al.*, 2010). Therefore, in response to the identified need for global observations, several satellite based instruments dedicated to the monitoring of the lower and middle atmosphere have been embarked in the past (see Table S2). Satellite measurements of atmospheric chemical constituents have enhanced our understanding of how human activities affect climate in the Earth system (Warner *et al*., 2010).

This section gives an overview of satellite based measurements of gas emissions and concentrations in the Earth atmosphere system.

3.5.1. *Carbon dioxide (CO_2)*

To predict the future carbon dioxide (CO_2) concentration in the atmosphere, and the resulting radiative forcing of climate change, knowledge of current CO_2 sources and sinks, their spatial distribution and variability is essential (Crevoisier *et al*., 2009b). Satellite measurements of the distribution of global atmospheric CO_2 concentration can contribute to such knowledge. Information on CO_2 atmospheric distribution can be retrieved from thermal infrared sounders (Chédin *et al*., 2002, 2003; Crevoisier *et al*., 2004; Engelen *et al*., 2004; Chahine *et al*., 2006; Maddy *et al*., 2008; Strow and Hannon, 2008) and from near infrared remote sensing (Buchwitz *et al*., 2005a; Barkley *et al*., 2007; Schneising *et al*., 2008). The Atmospheric Infrared Sounder (AIRS) together with the Advanced Microwave Sounding Unit (AMSU) on board the NASA/Aqua satellite has brought new insights to CO_2 monitoring from space (Chahine *et al*., 2006). A set of 43 AIRS channels, located in the CO_2 absorption bands, near 15 and 4.3 μm are considered in the Optimum Sensitivity Profile method (Crevoisier *et al*., 2003). These channels are characterized by a strong sensitivity to CO_2 variations and a low sensitivity to other atmospheric components and surface characteristics.

3.5.2. *Methane (CH_4)*

Methane (CH_4) is second only to carbon dioxide (CO_2) as an anthropogenic greenhouse gas (IPCC, 2007). However, the exact location, intensity and nature of methane sources and sinks are still not fully elucidated. For these reasons it is essential to have more knowledge of current CH_4 sources and sinks, their spatio-temporal distribution and variability to make projections of future CH_4 concentrations in the atmosphere (Crevoisier *et al*., 2009a). To fulfill this task, several remote sensing instruments have been embarked on satellite platforms to gain information on the distribution of methane in various parts of the atmosphere. For example, total columns of methane have been retrieved from SCIAMACHY data (Buchwitz *et al*., 2006; Carmo *et al*., 2006; Frankenberg *et al*., 2006, 2008). The SCIAMACHY methane distributions present high concentrations in the tropical region, which are possibly related to methane emission from terrestrial plants (Keppler *et al*., 2006). The CH_4 retrieval algorithm for AIRS is presented in Susskind *et al.* *(* 2003). The atmospheric temperature profile, water profile, surface temperature and surface emissivity required as inputs are derived from appropriate AIRS channels. For the CH_4 retrieval, these data plus a first-guess profile of CH_4 are used as inputs to the forward model (Strow *et al*., 2003) to compute the upwelling radiance (Susskind *et al*., 2003, 2006; Xiong *et al*., 2008). Ravazi *et al*. (2009) describe a method to retrieve methane concentrations from IASI. The inversion model is based on the Optimal Estimation Method (OEM) (Rodgers, 2000). Space-borne instruments working in a limb viewing geometry (e.g. MIPAS) add information on the vertical distribution of methane but are only sensitive from the upper troposphere to higher altitudes (Park *et al*., 2004; Raspollini *et al*., 2006; De Maziere *et al*., 2008).

3.5.3. *Carbon monoxide (CO)*

In recent years, extensive CO observations from a number of satellite platforms have yielded a global view of the CO distribution (George *et al*., 2009). Limb-sounders such as MIPAS/ENVISAT (Funke *et al*., 2007) or MLS/AURA (Pumphrey *et al*., 2007; Livesey *et al*., 2008) provide vertically resolved profiles for the mid/high-troposphere.

The MOPITT CO retrieval algorithm employs a non-linear optimal estimation method to solve iteratively for the CO profile, producing a result which is statistically most consistent with both the satellite-measured radiances and *a priori* information (Pan *et al*., 1998; Deeter *et al*., 2003). The current AIRS CO physical retrieval algorithm uses radiances in the 4.58–4.50 μm region and seeks to minimize the weighted difference between the clear column radiance observations and the radiance computed using the five AIRS forward model (SARTA) (Strow *et al*., 2003) by varying the geophysical state (Susskind *et al*., 2003).

3.5.4. *Ozone (O_3)*

The first spaceborne instruments for ozone measurements were the Solar Backscatter Ultraviolet (SBUV) and Total Ozone Mapping Spectrometer (TOMS) on NASA's Nimbus-7 satellite (Heath *et al*., 1975). The Solar Backscattered Ultraviolet model 2 instrument (SBUV/2) on the National Oceanic and Atmospheric Administration's NOAA-11 satellite has been providing global measurements of the total column ozone and the ozone profile since 1988 (Planet *et al*., 1994; Hilsenrath *et al*., 1995).

Takahashi *et al*. (1992) present a method for the derivation of the horizontal distribution of total ozone amounts from the brightness temperature data obtained by the HIRS/2 sensor on board the NOAA satellites. Chance *et al*. (1991, 1997) extended the ozone profile information to lower altitudes, including the troposphere, by using high spectral resolution hyperspectral data from GOME. Since then, several physically based retrieval algorithms were developed to retrieve ozone profiles from GOME radiances (Munro *et al*., 1998; Hoogen *et al*., 1999; Hasekamp and Landgraf, 2001; van der A *et al*., 2002; Liu *et al*., 2005). The operational algorithm for the retrieval of total ozone column from the GOME-2/MetOp is the GOME-2 Data Processor. In GDP the ozone slant columns are derived with a standard Differential Optical Absorption Spectroscopy retrieval (Loyola *et al*., 1997; Burrows *et al*., 1999; Spurr *et al*., 2005; van Roozendael *et al*., 2006; Valks and Loyola, 2008).

3.5.5. Nitrogen dioxide (NO_2)

Satellite observation of tropospheric NO_2 columns started in 1995 with the Global Ozone Monitoring Experiment (GOME-1) (Burrows *et al*., 1999). By using NO_2 data retrieved from GOME the influence of biomass burning, high lightning activity or soil emissions on the global distribution of tropospheric NO_2 is detectable (e.g. Leue *et al*., 2001; Richter and Burrows, 2002; Beirle *et al*., 2004; Jaegle *et al*., 2004). These observations are continued with GOME-2 (Callies *et al*., 2000), the SCanning Imaging Absorption spectroMeter for Atmospheric CHartographY (SCIAMACHY) (Bovensmann *et al*., 1999) and the Ozone Monitoring Instrument (OMI) (Levelt *et al*., 2006).

For OMI the standard NO_2 retrieval algorithm uses the Differential Optical Absorption Spectroscopy technique (Platt, 1994) to determine the slant column densities by nonlinear least squares fitting in the 415–465 nm window (Boersma *et al*., 2002; Bucsela *et al*., 2006; Celarier *et al*., 2008). Boersma *et al*. (2007) present a new near-real time technique for OMI to retrieve tropospheric NO_2 columns. The technique is based on a combined retrieval-assimilation-modelling approach for tropospheric NO_2 from the GOME and SCIAMACHY satellite instruments (Boersma *et al*., 2004).

3.5.6. Nitrogen monoxide (NO)

Data from GOME have also been used to retrieve global NO column amounts to study the behaviour of stratospheric NO (Wenig *et al*., 2004). Burrows *et al*. (1999) presented early results from GOME, which indicate enhanced NO over the populated areas of the Eastern United States and Europe. A new generation of satellite instruments now provides measurements of NO at spatial resolutions that exceed GOME resolutions by factors of seven or more (e.g. SCIAMACHY; Bovensmann *et al*., 1999).

3.5.7. Nitric acid (HNO_3)

Global distributions of HNO_3 in the stratosphere have been obtained from a series of limb-sounders operating in the infrared or millimetre spectral range. The first global observations of HNO_3 were based on the Limb Infrared Monitor of the Stratosphere (LIMS) launched on the Nimbus 7 spacecraft (Gille *et al*., 1980; Gille and Russell, 1984; Gille *et al*., 1984). The longest and the most complete observations of HNO_3 were measured by the Microwave Limb Sounder (MLS) on board the Upper Atmosphere Research Satellite (UARS) between 1991 and 1998 (Santee *et al*., 1995, 1999; Waters *et al*., 1999). These observations are complemented by MLS on the Aura satellite since 2004 (Santee *et al*., 2004; Urban *et al*., 2009), as well as by MIPAS (Stiller *et al*., 2003; Wang *et al*., 2007).

Two additional global HNO_3 observing instruments have recently been launched. The first is the Atmospheric Chemistry Experiment Fourier Transform Spectrometer (ACE-FTS) (Bernath *et al*., 2005) and the second is a follow-on version of the UARS MLS instrument that was also launched on the EOS Aura satellite (Waters *et al*., 2006; Santee *et al*., 2005, 2007).

3.5.8. Sulphur dioxide (SO_2)

Satellite-based SO_2 observations were first performed using the Total Ozone Mapping Spectrometer (TOMS) (Krueger, 1983). This was followed by other satellite sensors as GOME, SCIAMACHY and OMI (e.g. Krueger *et al*., 1995; Eisinger and Burrows, 1998; Carn *et al*., 2004; Richter *et al*., 2006; Yang *et al*., 2007; Krotkov *et al*., 2008).

TOMS, GOME and OMI algorithms use reflected ultraviolet sunlight to determine column SO_2 amounts (Prata *et al*., 2007). The Differential Optical Absorption Spectroscopy technique (Platt, 1994) has been successfully employed for SO_2 measurements on global and regional scales (e.g. Chance, 1998; Martin *et al*., 2002; Palmer *et al*., 2003; Wittrock *et al*., 2006; Lee *et al*., 2008).

Sulphur dioxide has a strong spectral absorption region centred near 7.4 μm, and a second, weaker, absorption region located near 8.7 μm (Ackerman *et al*., 2008). Spectral signature methods using measurements at 7.3, 8.5, 11, and 12 μm from the High-Resolution Infrared Radiation Sounder (HIRS) have been used successfully in detecting volcanic plumes (e.g. Baran *et al*., 1993; Ackerman and Strabala, 1994; Ackerman, 1997; Yu and Rose, 2000; Prata *et al*., 2003). High spectral resolution observations from AIRS are also used to analyse SO_2 plumes from volcanoes (e.g. Carn *et al*., 2005; Prata and Bernardo, 2007). Prata *et al*. (2007) used AIRS measurements to infer volcanic SO_2 concentrations in the upper troposphere. The algorithm relies on the strong SO_2 absorption feature near 7.3 μm and takes into account interference from water vapour across the band.

3.5.9. Sulphur monoxide (SO)

The first quantitative SO concentration data for a major volcanic eruption was obtained from the TOMS for the El Chichon eruption in 1982 (Krueger, 1983). All significant eruptions since 1978 have now been measured by the series of TOMS instruments (Bluth *et al*., 1992, 1993; Krueger *et al*., 1995, 2000; Schnetzler *et al*., 1997; Carn *et al*., 2003). Greatly improved sensitivity concerning volcanic and anthropogenic SO detection is provided by GOME and SCIAMACHY full spectrum UV data (Eisinger and Burrows, 1998; Bovensmann *et al*., 1999; Burrows *et al*., 1999). Infrared detection of volcanic SO has also been demonstrated with AIRS data (Carn *et al*., 2005), but IR sensors have low sensitivity to tropospheric and boundary layer SO emissions.

3.6. Profiles

Temperature sounding instruments on board polar-orbiting satellites provide high spatio-temporal resolution and enable a more reliable analysis of long term atmospheric temperature trends. Since 1978 atmospheric temperatures for the lower troposphere to the stratosphere have been retrieved through combined measurements in the 15 μm carbon dioxide (CO_2) absorption band from the High-Resolution Infrared Radiation Sounder (HIRS) and in the oxygen (O_2) absorption band around 60 GHz from the Microwave Sounding Unit (MSU) on board National Oceanic and Atmospheric Administration (NOAA) operational polar-orbiting satellites (Auman *et al*., 2003; Chung *et al*., 2010). In 1998 the MSU was replaced by the Advanced Microwave Sounding Unit (AMSU). The combination of HIRS/3, AMSU-A and AMSU-B constitutes the current operational sounding system of the National Oceanic and Atmospheric Administration (NOAA) (Auman *et al*., 2003). With channels in the oxygen absorption band, AMSU-A is designed to retrieve the atmospheric temperature profiles. AMSU-B module makes measurements in the vicinity of the strong water vapour absorption line at 183 GHz and is used for atmospheric water vapour sounding. Several retrieval techniques have been developed for temperature and/or humidity sounding with AMSU-A/B and other microwave radiometers measurements (see Table S2). Radiation measurements from layers as high as the lower stratosphere (Channel 1: 14.7 μm) down to the surface (Channel 8: 11.0 μm) from GOES Sounder enable to derive vertical variations of temperature, moisture, and total column ozone (Smith, 1983; Hayden, 1988; Ma *et al*., 1999; Li *et al*., 2001). The operational MODIS atmospheric profile algorithm uses 12 infrared bands with wavelengths between 4.47 and 14.24 μm that are related to MODIS infrared band radiances calculated from more than 8400 global radiosonde profiles of temperature, moisture and ozone (King *et al*., 2003).

Weisz *et al*. (2007) present an AIRS alone single field of view retrieval algorithm to simultaneously retrieve temperature, humidity and ozone profiles under all weather conditions. A fast cloudy radiative transfer model accounting for clouds of various phases, cloud particle sizes and optical thicknesses was used to simulate cloudy radiances representing the regression training set.

The HIRDLS algorithm to retrieve atmospheric temperature and humidity profiles is based on the optimal estimation solution technique for inverse problems (Rodgers, 2000) that relates forward radiative transfer model calculated radiances with those observed (Khosravi *et al*., 2009).

Amato *et al*. (2009) propose a retrieval algorithm that uses a statistical strategy based on dimension reduction for the IASI instrument to retrieve atmospheric profiles of temperature, water vapour and ozone.

3.7. Aerosols

Aerosols in the troposphere are a major climate forcing parameter, due to the direct and indirect aerosol effect (Twomey *et al*., 1984; Kaufman and Nakajima, 1993; Ramaswamy, 2001). Despite this importance there are still significant uncertainties concerning the physical and optical properties of tropospheric aerosols and their interaction with global climate (IPCC, 2007). This is mainly due to the inadequate quantitative knowledge of global aerosol characteristics and their temporal variability (Bates *et al*., 2006; Penner *et al*., 2006; Li *et al*., 2009). To evaluate the aerosol radiative effects together with the magnitude and the potential variability of the aerosol climate forcing it is therefore essential to monitor aerosols on the global scale (Kiehl and Briegleb, 1993; Taylor and Penner, 1994). In this context, passive and active satellite sensors have been used to retrieve global distributions of aerosol properties (see Table S2). Overviews of existing retrieval algorithms can be found in King *et al*. (1999), Yu *et al*. (2006), Mishchenko *et al*. (2007), Fishman *et al*. (2008), and Tanré (2010).

The most relevant parameters to characterize aerosol properties and distribution and that are accessible from satellite data are the aerosol optical depth (AOD), a measure of the integrated aerosol load through the atmosphere, and the Angstrom Exponent (AE), which is related the spectral dependence of the AOD and is a measure for the column integrated aerosol size distribution (Tanré, 2010).

Satellite-based AOD retrieval has been successfully applied over oceans by using the low reflectance of oceans at solar wavelengths in the red and near-infrared spectral regions (Griggs, 1983; Stowe *et al*., 1997; Tanré *et al*., 1997).

Aerosol retrieval over land is more complicated due the higher and more variable surface reflectance. Since the measured signal consists of sunlight reflected by both the Earth's surface and the aerosol layer, some assumptions about the surface reflectance properties and aerosol properties have to be made to separate the aerosol contribution to the signal from that of the surface (Kaufman *et al*., 2002). Algorithms for the successful AOD retrieval over land were developed by e.g. Kaufman and Sendra (1988), Fraser *et al*. (1992), and Kaufman *et al*. (1997).

The first satellite based aerosol studies used data from geostationary satellites (GOES, METEOSAT), or from polar orbiting platforms (NOAA/AVHRR series) (e.g. Fraser *et al*., 1984; Husar *et al*., 1997). The near-daily global coverage from the MODIS AOD retrieval provides a high temporal resolution and uses multiple MODIS channels and separate algorithms for ocean (Tanré *et al*., 1997) and land (Kaufman *et al*., 1997; Remer *et al*., 2005). The algorithms are continuously validated and updated (Hsu *et al*., 2004; Levy *et al*., 2005, 2007; Li *et al*., 2007; Remer *et al*., 2007).

The additional angular information from the MISR AOD retrieval (Diner *et al*., 2005; Martonchik *et al*.,

2009) allows reduction of algorithmic assumptions and retrieval bias (Kahn *et al*., 2007). The MISR product consists of the AOT, Angstrom exponent and aerosol type retrieved over both land and the oceans (Mishchenko *et al*., 2007).

The ATSR-2 and AATSR sensors on ENVISAT uses two view directions in a wide spectral range (0.55–1.65 μm) to measure aerosol properties and their distribution (Veefkind *et al*., 1998, North *et al*., 1999; Grey *et al*., 2006). The retrieval of aerosol properties over land from POLDER is based on polarized reflectance measurements (Deuze *et al*., 1999, 2000). Scattering by aerosol particles generates highly polarized light (Deuze *et al*., 1999) which makes the polarized satellite radiances more sensitive to the presence of aerosols. The new generation of satellite based high spectral resolution infrared sounders AIRS and IASI are well suited to retrieve aerosol properties such as optical depth, altitude and mean particle size (Pierangelo *et al*., 2005; Peyridieu *et al*., 2010). The algorithms are based on the fact that long wave channels (8–12 μm) are sensitive to both the AOD and the altitude of the dust layer while short wave channels (around 4 μm) are essentially sensitive to the dust optical depth. The aerosol algorithm for OMI (Torres *et al*., 2007) makes use of the full UV-to-visible spectral coverage to derive spectral aerosol extinction optical depth. It uses forward calculations for a number of microphysical aerosol models defined by the size distribution and the complex refractive index as well as the AOD and the aerosol layer height.

Algorithms to retrieve aerosol vertical structure by using CALIPSO CALIOP has been successfully implemented by Winker *et al*. (2007), Kim *et al*. (2008), and Vaughan *et al*. (2009). Chand *et al*. (2008) examine two techniques for CALIPSO to deduce AOD and the Angstrom exponent directly from aerosol effects on light transmissions. Josset *et al*. (2008) retrieve AOD over oceans by combining CALIOP and Cloudsat measurements (Stephens *et al*., 2002). The combination of spectral measurements from MODIS with active lidar measurements provided by CALIPSO CALIOP allows the derivation of information on the aerosol size distribution along the vertical atmospheric path (Kaufman *et al*., 2003; Leon *et al*., 2003).

3.8. Clouds

3.8.1. Cloud classification

Identifying clouds in satellite imagery is an important first step in the retrieval of both surface and atmospheric properties (Berendes *et al*., 1999). In the past, various cloud classification techniques have been developed for the different satellite systems and for a variety of purposes (see Table S2). Pankiewicz (1995) and Bankert *et al*. (2009) give an extensive review of satellite based cloud classification research.

Most commonly, spectral and/or textural features are used for cloud classification. Spectral features are generally more important. They make use of the information on the cloud radiance in different spectral bands. Some of the most commonly used methods in this category include threshold based schemes (e.g. Bendix *et al*., 2004), multi-spectral approaches and histogram schemes. Famous threshold-based algorithms developed for NOAA-AVHRR data are the APOLLO scheme (Saunders, 1986; Saunders and Kriebel, 1988; Kriebel *et al*., 2003) or the multispectral cloud analysis scheme SCANDIA (Karlsson, 1989, 1996). Approaches using one-dimensional and/or multidimensional histogram techniques are presented by Desbois *et al*. (1982), Simmer *et al*. (1982), Phulpin *et al*. (1983), and Kärner (1997).

Because of their physical importance, spectral features have proven to be effective and simple. However, they also encounter some problems because of the spectral similarities of certain objects such as ice cloud and snow. Other factors, such as moisture in the atmosphere, may also alter the multi-spectral characteristics and thus affect the classification result (Kaur and Ganju, 2008).

Textural features distinguish different cloud types by the spatial distribution characteristics of gray levels corresponding to a region in one specific channel. While the spectral characteristics of clouds may change, their textural properties are often distinct and tend to be less sensitive to the effects of atmosphere (Kaur and Ganju, 2008). For example, Coakley and Bretherton (1982) applied tests on spatial coherence to detect cloud-filled pixels and classify the cloud type (low, medium, high cloud, thin cirrus).

Fuzzy logic and neural network approaches were explored for cloud classification e.g. by Baum *et al*. (1997), Lewis *et al*. (1997), Miller and Emery (1997), Tian *et al*. (1999), McIntire and Simpson (2002), and Ghosh *et al*. (2006).

The National Oceanic and Atmospheric Administration Clouds from AVHRR algorithm incorporates multispectral information, channel differences, and spatial differences and applies a series of sequential decision tree tests (Stowe *et al*., 1991, 1999) to identify cloud-free, mixed and cloudy regions in the image. The MODIS cloud mask algorithm uses a series of sequential cloud detection tests to indicate a level of confidence that MODIS is observing a clear-sky scene (Ackerman *et al*., 1998; King *et al*., 2003; Platnick *et al*., 2003; Frey *et al*., 2008).

Breon and Colzy (2000) describe a cloud screening algorithm for the POLDER instrument over land surfaces. Four tests are applied to the measurements. First a threshold on the 0.44 μm reflectance after atmospheric correction is applied. Second a similar but smaller threshold is applied only over targets with significant spectral variation. Third the surface pressure is compared to an estimate derived from two POLDER channels centred on an oxygen absorption band. The final test makes use of POLDER polarization capabilities and seeks the presence of a rainbow generated by water clouds.

There are some algorithms to identify multilayer clouds with passive imagers. Pavolonis and Heidinger (2004) developed a pixel-level algorithm applicable to AVHRR and MODIS that uses ratios and differences of reflectances and brightness temperatures in various bands. The algorithm introduced by Baum *et al.* (2000) and Nasiri and Baum (2004) is a statistically based algorithm for MODIS that retrieves a multilayer cloud probability for a box area of user defined size. The MODIS operational multilayer cloud detection algorithm considers the difference between above-cloud precipitable water obtained from using the 0.94 µm band and above-cloud precipitable water retrieved from the CO_2 slicing–derived cloud-top altitude to determine whether the cloud is multilayered (Wind *et al.*, 2010).

Specific algorithms have been developed for the detection of fog/low stratus (NOAA: Bendix, 2002; MODIS: Bendix *et al.*, 2006; MSG: Cermak and Bendix, 2007, 2008) and ground fog (Bendix *et al.*, 2005; Cermak and Bendix, 2011) on different LEO and GEO sensors, using VIS to MIR spectral information.

3.8.2. *Cloud properties*

Clouds play in important role in the atmospheric radiation budget and in the global hydrological cycle and, since they act as a key modifier of the global climate, the IPCC emphasized the need for more global measurements on cloud properties to investigate the corresponding radiative fluxes and forcing (IPCC, 2007).

Typical cloud parameters that can be derived from satellite data and that are useful for such investigations comprise cloud-top height, cloud optical thickness, cloud effective particle radius, cloud liquid water path and cloud phase (Reuter *et al.*, 2009).

Several techniques for the retrieval of cloud-top pressure/height (CTP/CTH) have been developed (see Table S2). The most common technique is to obtain a satellite-based measure of the thermal cloud-top brightness temperature. These temperature measurements are obtained in the infrared window wavelength of 10–12 µm and are compared to corresponding temperature profile data to determine the cloud-top height (Fritz and Winston, 1962; Smith and Platt, 1978). Another approach, known as the CO_2 slicing technique, considers the cloud's emission within the carbon dioxide (CO_2) absorption channels around 14 µm to derive the cloud-top temperature (Wielicki and Coakley, 1981; Menzel *et al.*, 1983, 2002). The cloud-top height is inferred by comparing the retrieved cloud-top temperature with corresponding atmospheric temperature and humidity profiles (Frey *et al.*, 1999). The CO_2 slicing technique has a long tradition. It was first applied to the High Resolution Infrared Radiometer Sounder (HIRS; Wylie and Menzel, 1999) and the Geostationary Operational Environmental Satellite (GOES) sounder (Menzel *et al.*, 1992; Menzel and Purdom, 1994).

A further method, which is applied to Medium-Resolution Imaging Spectrometer (MERIS) data, is based on measurements of the cloud-reflected solar radiation within the oxygen A band around 761 nm (Fischer and Grassl, 1991).

The MISR CTH retrieval is based on cloud detection by cameras at two different angles and positions. The height of the cloud relative to the surface is calculated from the apparent change in position (Diner *et al.*, 1999; Moroney *et al.*, 2002; Muller *et al.*, 2002; Chae and Sherwood, 2010).

The CALIPSO cloud data product provide the number of vertical cloud layers and the cloud top and cloud base height for each of these layers (Stubenrauch *et al.*, 2010). The cloud profiling radar (CPR) of the CloudSat mission (Stephens *et al.*, 2002; Mace *et al.*, 2007) also provides information on vertical cloud layer structure. For a complete picture of the vertical cloud structure, the Cloudsat Geometrical Profiling Product (Mace *et al.*, 2007; Marchand *et al.*, 2008) and the CALIPSO Vertical Feature Mask (Vaughan *et al.*, 2004) have been merged into a combined Radar-Lidar Geometrical Profile Product (Mace *et al.*, 2009).

Cloud microphysical retrievals using visible and near-infrared channels rely on the fact that the reflection function at the non-absorbing wavelength is mainly a function of the cloud optical thickness, and the reflection at an absorbing wavelength is largely determined by the effective radius. The retrieval techniques are based on the 1-D radiation concept where a cloud is regarded as a plane-parallel, vertically and horizontally homogeneous layer which completely covers a remotely sensed picture element. The general principles of inversion theory in terms of cloud microphysics retrievals are presented and discussed by Twomey and Seton (1980). The retrieval of cloud optical properties from multispectral satellite data include studies by Arking and Childs (1985), Twomey and Cocks (1989), Nakajima *et al.* (1991) and Minnis *et al.* (1992a, 1992b). Satellite-based algorithms to retrieve cloud properties generally use some kind of look-up table (LUT) approach (e.g. Nakajima and King, 1990; Han *et al.*, 1994; Nakajima and Nakajima, 1995). Pre-calculated radiative transfer results are iteratively matched with actual measured values in the visible and near-infrared channels.

Various algorithms have been developed to retrieve cloud optical thickness and cloud effective particle radius. Most of the retrieval techniques have been developed for optical sensors aboard polar-orbiting satellites (e.g. King *et al.*, 1997; Platnick *et al.*, 2003). Techniques are also available for geostationary satellite systems (e.g. Han *et al.*, 1994; Feijt *et al.*, 2004; Roebeling *et al.*, 2006, 2008).

Chang and Li (2002, 2003) proposed a technique to estimate the vertical profile of droplet effective radius for water clouds using multispectral near-infrared measurements from MODIS. The underlying principle of the retrieval technique is that radiance measurements at different near infrared wavelengths possess different penetration depths inside the cloud, providing information on the vertical profile of the effective radius. Kokhanovsky *et al*. (2005) present a cloud retrieval algorithm, which is based on the two-wavelength semi-analytical cloud retrieval algorithm for the liquid water path and the cloud particle size determination proposed by Kokhanovsky *et al*. (2003). Kokhanovsky *et al*. (2006) developed a new technique to identify mixed-phase clouds and clouds with supercooled water droplets. The technique uses AATSR and SCIAMACHY data and is based on measurements of the backscattered solar light at wavelengths 1.55 and 1.67 m in combination with cloud brightness temperature measurements at 12 μm. Greenwald *et al*. (1997) derived the first estimates of the cloud liquid water path and the droplet effective radius for marine stratocumulus clouds using the GOES-8 imager.

For cirrus clouds there are also algorithms depending only on the infrared channels (Ackerman *et al*., 1990; Strabala *et al*., 1994). Yang *et al*. (2007) use a bispectral technique based on pre-calculated lookup tables of ice cloud radiances to infer the optical thickness and effective particle size of an ice cloud from the MODIS measurements during daytime.

The polarization characteristics in the visible and near-infrared spectral region from POLDER can be used to retrieve cloud properties (Chepfer *et al*., 1998, 1999; Breon and Colzy, 2000; Masuda *et al*., 2002). Liou and Takano (2002) demonstrated that information on ice crystal shape and crystal orientation can be inferred from the reflected polarization patterns.

Night time algorithms for cloud property retrievals are also available (Baum *et al*., 1994, 2003; Minnis *et al*., 1998; Perez *et al*., 2000; Wong *et al*., 2007; Merk *et al*., 2010). Generally, these algorithms are based on the concept of effective emissivity (Platt and Stephens, 1980; Liou *et al*., 1990). Because of the exponential relationship between optical depth and emissivity the maximum retrievable optical thickness is about 6–8 (Liou *et al*., 1990; Minnis *et al*., 1998). Han *et al*. (2009) developed a new IR technique based on direct radiative transfer calculations, which extends the range of the retrievable optical depth and enables the use of instantaneous atmospheric profiles for improving retrieval accuracy. Compared to other passive remote sensing instruments, the high spectral resolution of IR vertical sounders such as the AIRS leads to especially reliable properties of cirrus with optical depth as low as 0.1, day and night (e.g. Stubenrauch *et al*., 1999, 2006; Kahn *et al*., 2007).

Retrievals of cloud liquid water path (LWP) using visible and near infrared channels depend on the assumed droplet size distribution and its vertical variation. These techniques are prone to non-plane parallel and solar/viewing geometry effects in retrieving microphysical cloud properties (Varnai and Marshak, 2002; Marshak *et al*., 2006; Kato and Marshak, 2009). Retrieval techniques relying on passive microwave observations are prone to uncertainties in cloud temperature, surface emissivity, atmospheric absorption and the assumed temperature/humidity structure of the lower atmosphere, as well as to the effects of sub-field-of-view clouds (Greenwald *et al*., 2007; Stephens and Kummerow, 2007; Horvath and Gentemann, 2007; Zuidema and Joyce, 2008).

A great variety of LWP retrieval algorithms have been introduced since the first SSM/I was launched (e.g., Petty, 1990; Bauer and Schluessel, 1993; Greenwald *et al*., 1993; Liu and Curry, 1993; Lin and Rossow, 1994; Weng and Grody, 1994; Jung *et al*., 1998).

Wentz and Meissner (2000) use the liquid-sensitive 37 GHz channel measurements of AMSR-E to retrieve LWP products. Zhao and Weng (2002) developed an algorithm to derive cloud ice water path and ice particle effective diameters from AMSU measurements. Both parameters are related to the ice particle scattering parameters, which are determined from the AMSU 89 and 150 GHz measurements. The ratio of the scattering parameters measured at two frequencies provides a direct estimate of the ice particle effective diameter.

Hu *et al*. (2009) introduced an improved cloud phase determination algorithm using the active system CALIPSO. Based on theoretical and modelling studies, the algorithm differentiates cloud phases by using the spatial correlation of layer-integrated attenuated backscatter and layer-integrated particulate depolarization ratio. Yoshida *et al*. (2010) introduce a method for discriminating cloud particle types for CALIOP on CALIPSO. The authors theoretically estimated the relationship between the depolarization ratio and cloud extinction on the basis of the backward Monte Carlo method.

3.9. Precipitation

Precipitation is a key factor of the global water cycle and affects all aspects of human life. Because of its great importance and its high spatial and temporal variability, the correct spatio-temporal detection and quantification of precipitation has been one of the main goals of meteorological satellite missions. Precipitation retrieval from satellite data can provide area-wide information in regions for which data from rain gauge or radar networks are sparse or unavailable (Kuligowski, 2002). During the last decades several satellite-based rainfall retrieval algorithms have been developed (see Table S2). A comprehensive overview of existing satellite-based rainfall retrieval methods can be found in Kidder and Vonder Haar (1995), Kidd (2001), Levizzani *et al*. (2001), Levizzani (2003), Scofield and Kuligowski (2003), Anagnostou (2004), Stephens and Kummerow (2007), and Kidd and Levizzani (2011). An overview of existing retrieval techniques based on passive microwave sensors can be found in Wilheit *et al*. (1994), Petty (1995), Kummerow *et al*. (2001), Levizzani *et al*. (2002), Weng *et al*. (2003), and Joyce *et al*. (2004). Regarding explanations of the Tropical Rainfall Measuring Mission (TRMM) precipitation radar (PR), the reader is referred to Iguchi *et al*. (2000) and Ferreira *et al*. (*2001)*. The following overview is arranged by the complexity of the algorithms according to Barrett and Martin (1981).

Cloud index methods use thresholds for IR cloud-top temperature to detect rain areas, to which a rainfall rate is assigned. The most popular cloud index method is the Geostationary Operational Environmental Satellite (GOES) precipitation index (GPI; Arkin and Meisner, 1987), which uses a cloud-top temperature of 235 K as a threshold to delineate precipitating clouds. A constant rainfall rate is assigned to these raining pixels.

Feature-based methods rely on the assumption that the relationship between the satellite cloud-top brightness temperature and surface rainfall rate is not unique for most pixel-based rainfall estimation algorithms. Feature-based classification schemes use IR cloud-top temperature to classify different cloud types. The relationship between cloud top temperature and rainfall rate is retrieved for respective classified cloud types (e.g. Wu *et al*., 1985; Hsu *et al*., 2002; Bellerby, 2004). The Precipitation Estimation from Remotely Sensed Information Using Artificial Neural Networks (PERSIANN) Cloud Classification System algorithm by Hong *et al.* (2004) first separates 10.7 µm cloud images into distinctive cloud patches and then extracts different cloud features. The cloud patches are clustered into subgroups, which the rainfall rate is assigned to as a function of cloud-top IR temperature.

Multispectral methods are based on the assumption that precipitating clouds have a high VIS reflectivity and a cold IR cloud-top temperature, which is ideally valid for deep convective clouds. A prominent example is the 'RAINSAT' algorithm developed by Lovejoy and Austin (1979) and Bellon *et al.* (1980). Lensky and Rosenfeld (1997) and Rosenfeld and Lensky (1998) used the 3.7 µm reflectance and the 11 µm brightness temperature to detect rain areas and estimate rainfall rates. Capacci and Porcu (2009) present a daytime surface rain-rate classifier for MSG SEVIRI, based on artificial neural networks trained with data from ground based radar networks. The GOES multispectral rainfall algorithm (Ba and Gruber, 2001) combines information from five channels for the detection of precipitating cloud areas. The rainfall rate is assigned by the product of rainfall probability and mean rainfall rate, calculated as a function of the 11 µm temperatures.

Life cycle methods consider the temporal variability of convective systems and the involved precipitation processes. Griffith *et al.* (1978) used the cloud-top temperature difference between two consecutive scenes as a measure for the activity of convective clouds. Negri *et al.* (1984) classified different life cycles of convective clouds based on a single scene and attained comparable results to Griffith *et al.* (1978).

Cloud model techniques try explicitly to consider the physical processes that clouds undergo. The assigned rainfall rates are based on numerically simulated cloud-top temperatures and the corresponding rainfall rate (Gruber, 1973; Wylie, 1979). Based on studies of Adler and Mack (1984), Adler and Negri (1988) developed the Convective Stratiform Technique (CST) for subtropical convective systems which has been successfully applied also to tropical rain systems (Bendix, 1997). The CST has become a widely used and intensively validated technique.

Despite the variety of existing satellite-based rainfall retrieval techniques, most retrieval schemes developed for Geostationary Earth Orbit (GEO) systems rely on a relationship between IR cloud-top temperature, rainfall probability and rainfall rate. Such IR retrievals are appropriate for convective clouds that can easily be identified by their cold cloud-top temperature in the IR channel (e.g. *Levizzani et al*., 2001; Levizzani, 2003), but show considerable drawbacks concerning the detection and quantification of rain from stratiform clouds in connection with extratropical cyclones (e.g. Ebert *et al*., 2007; Früh *et al*., 2007). Such precipitating clouds are characterized by relatively warm and spatially homogeneous cloud-top temperatures that differ insignificantly from raining to non-raining regions. Therefore, retrieval techniques based solely on IR cloud-top temperature lead to an underestimation of the detected rain area and to uncertainties concerning the assigned rainfall rate (e.g. Ebert *et al*., 2007).

To overcome these drawbacks, several authors suggest using optical and microphysical cloud parameters derived from multispectral data of new generation satellite systems to improve rainfall retrievals (e.g. Ba and Gruber, 2001; Lensky and Rosenfeld, 2003a, 2003b; Nauss and Kokhanovsky, 2006, 2007; Thies *et al*., 2008a, 2008b, 2008c; Roebeling and Holleman, 2009; Küehnlein *et al*., 2010). They could show that cloud areas with a high optical thickness and a large effective particle radius possess a high amount of cloud water and are characterized by a higher rainfall probability than cloud areas with a low optical thickness and a small effective particle radius.

Microwave radiances are related more directly to precipitation rates. Rainfall retrievals using data from satellite microwave radiometers are more physically based on the relationship between the observed microwave brightness temperatures and the available liquid water within the cloud (Levizzani *et al*., 2007). Different microwave sensors have been used in the past for satellite-based rainfall retrieval. Among them there are the Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI), the Special Sensor Microwave Imager (SSM/I), and the Advanced Microwave Scanning Radiometer (AMSR). Since the early Special Sensor Microwave Imager (SSM/I) retrievals a number of algorithms have been developed. Prominent SSM/I based rainfall retrieval techniques are the NOAA/NESDIS algorithm (Grody, 1991; Ferraro and Marks, 1995; Ferraro, 1997; McCollum and Ferraro, 2003; Dinku and Anagnostou, 2005) and the Goddard scattering algorithm (Adler *et al*., 1994).

The most recent rainfall retrieval algorithms rely on the 98 and 150 GHz window channels of AMSU data (e.g. Weng and Grody, 2000; Bennartz *et al*., 2002; Zhao and Weng, 2002; Chen and Staelin, 2003; Ferraro *et al*., 2005). Di Tomaso *et al*. (2009) propose a technique based entirely on the observations made by AMSU/B. The method incorporates the measurements at 89 and 150 GHz (window channels) and the signal received in the 183 GHz water vapour band (opaque channels).

The differences between the measurements are analysed through radiative transfer simulations for the estimation of precipitation over both land and water surfaces and are related to rain rate values in different atmospheric scenarios. The Goddard Profiling algorithm (GPROF; Kummerow *et al*., 2001) is one of the most successful techniques in this category. The GPROF algorithm is an inversion-type algorithm providing estimates of instantaneous rainfall rates, the vertical structure of precipitation and the associated latent heating. The algorithm is based on large databases of cloud model derived profiles which are used for radiative transfer calculations at cloud model resolution (Kummerow and Giglio, 1994; Kummerow *et al*., 2001; Masunaga and Kummerow, 2005).

Mitrescu *et al*. (2010) developed a technique to retrieve light precipitation from CloudSat's millimetre-wavelength Cloud Profiling Radar (CPR) measurements. The radar model relies on the description of clouds and rain particles in terms of a drop size distribution function. Berg *et al*. (2010) use a combination of rainfall estimates from the 13.8-GHz TRMM PR (Iguchi *et al*., 2000) and the 94 GHz CloudSat Cloud Profiling Radar (Haynes *et al*., 2009) to assess the distribution of rainfall intensity over tropical and subtropical oceans. The PR provides the total rain volume because of its ability to estimate the intensity of all but the lightest rain rates, while the higher sensitivity of the CloudSat radar provides estimates of drizzle and light rain.

While satellite-based rain rate estimates are reliable and operational (Olson *et al*., 1996, 2006; Ferraro *et al*., 2005), the measurement of snowfall rates from space is a relatively new field (Chen and Staelin, 2003; Kongoli *et al*., 2003; Liu, 2004; Skofronick-Jackson *et al*., 2004; Noh *et al*., 2006). One major challenge associated with retrieving snowfall rates are the complex macrophysical and microphysical features of snow clouds (Kim *et al*., 2008). Kim *et al*. (2008) present a physical model to retrieve snowfall rate over land using brightness temperature observations from AMSU-B at 89, 150, 183.3, 183.3 and 183.3 GHz.

Many algorithms show encouraging results by combining data from IR and PMW sensors (e.g. Adler *et al*., 1993; Kummerow and Giglio, 1995; Miller *et al*., 2001b; Todd *et al*., 2001; Turk *et al*., 2003; Huffman *et al*., 2007; Bellerby *et al*., 2009; Hsu *et al*., 2009). The self-calibrating multivariate precipitation retrieval (Kuligowski, 2002) is another multisensor approach, which adds the dimension of being calibrated in real time against rain rates from PMW sensors. Other retrieval techniques developed in the past several years, are the Climate Prediction Center (CFC) morphing algorithm (CMORPH; Joyce *et al*., 2004), the Naval Research Laboratory Global Blended-Statistical Precipitation Analysis (NRLgeo; Turk and Miller, 2005), the Passive Microwave-Calibrated Infrared algorithm (PMIR; Kidd *et al*., 2003), and the Precipitation Estimation from Remotely Sensed Information Using Artificial Neural Networks (PERSIANN; Sorooshian *et al*., 2000). Adler *et al*. (2000, 2003) describe a technique to use TRMM combined PR-TMI measurements to adjust geostationary IR data (the TRMM Adjusted Geostationary Operational Environmental Satellite Precipitation Index (AGPI)). Layberry *et al*. (2006) introduce a high-resolution multiplatform multisensor satellite rainfall product for southern Africa. The microwave infrared rainfall algorithm (MIRA) combines high spatial and temporal resolution Meteosat IR data with infrequent SSM/I overpasses. A transfer function relating Meteosat thermal infrared cloud brightness temperatures to SSM/I rainfall estimates is derived using collocated data from the two instruments and is then applied to the full coverage of the Meteosat data. The TMPA 3B42RT product (Huffman *et al*., 2007) is a near-real-time precipitation rate product at time and space scales. This product makes use of TRMM PR/TMI observations, along with high quality passive microwave-based rain estimates from three to seven polar-orbiting satellites (e.g., AMSR-E, SSMI/DMSP, AMSU-A), and all the geostationary IR sensors (e.g., Meteosat, GOES, GMS). The combined quasi-global rain map at 3 h resolution is produced by using TRMM to calibrate the estimates from all the other satellites and then combining all the estimates into the TMPA final product.

4. Conclusions

Operational satellite systems provide valuable information on atmospheric parameters at regular intervals on a global scale. This satellite-based information about the Earth-atmosphere system and its components greatly enhance our knowledge and understanding of the processes and dynamics within the Earth-atmosphere system.

The current paper presents the development of meteorological satellites and techniques to retrieve information for weather forecast and climate research, ranging from the beginning of meteorological remote sensing to the near future of approved next-generation satellite systems. Successful instruments from experimental LEO systems have been improved and transferred to the next generation of operational LEO systems, while proven instruments from operational LEO systems have made it on board follow-up GEO systems.

Future satellite systems must sustain the observational capabilities of key global climate parameters. On the one hand this involves the improvement and further development of operational missions, critical for routine weather observation and numerical weather forecast. On the other hand this also implies the continuation of existing and established systems to assure the provision of long-term data sets for climate monitoring.

Beside the numerical weather prediction and climate monitoring, another important field of application is the global hydrological cycle. In this context improved observation capabilities concerning the water cycle and the interactions of its respective components are needed. A further important topic is the investigation of CO_2 sources and sinks as well as the analysis of other greenhouse gases. In this context observations on regional scales with high accuracy are still of major priority.

Supporting information

The following supporting information is available as part of the online article:
Table S1. Existing LEO and GEO satellite systems and meteorological parameters.
Table S2. Overview of meteorological parameters retrieved from satellite based sensors.

References

van der A RJ, van Oss RF, Piters AJM, Fortuin JPF, Meijer YJ, Kelder HM. 2002. Ozone profile retrieval from recalibrated GOME data. *Journal of Geophysical Research* **107**: 4239.

Ackerman SA. 1997. Remote sensing aerosols from satellite infrared observations. *Journal of Geophysical Research* **102**: 17069–17079.

Ackerman SA, Schreiner AJ, Schmit TJ, Woolf HM, Li J, Pavolonis M. 2008. Using the GOES Sounder to monitor upper level SO2 from volcanic eruptions. *Journal of Geophysical Research* **113**: D14S11.

Ackerman SA, Smith WL, Collard AD, Ma XL, Revercomb HE, Knuteson RO. 1995. Cirrus cloud properties derived from high-spectral resolution infrared spectrometry during FIRE II, Part II: aircraft HIS results. *Journal of the Atmospheric Sciences* **52**: 4246–4263.

Ackerman SA, Smith WL, Spinhirne JD, Revercomb HE. 1990. The 27–28 October 1986 FIRE IFO cirrus case study: spectral properties of cirrus clouds in the 8–12 Am window. *Monthly Weather Review* **118**: 2377–2388.

Ackerman SA, Strabala KI. 1994. Satellite remote sensing of H2SO4 aerosol using the 8 to 12 mm window region: application to Mount Pinatubo. *Journal of Geophysical Research* **99**: 18639–18649.

Ackerman SA, Strabala KI, Menzel WP, Frey RA, Moeller CC, Gumley LE. 1998. Discriminating clear-sky from clouds with MODIS. *Journal of Geophysical Research: Atmosphere* **103**(D24): 32141–32157.

Adams IS, Hennon CC, Jones WL, Ahmad KA. 2006. Evaluation of hurricane ocean vector winds from WindSat. *IEEE Transactions on Geoscience and Remote Sensing* **44**: 656–667.

Adler RF, Huffman GJ, Bolvin DT, Curtis S, Nelkin EJ. 2000. Tropical rainfall distributions determined using TRMM combined with other satellite and rain gauge information. *Journal of Applied Meteorology* **39**: 2007–2023.

Adler RF, Huffman GJ, Chang A, Ferraro R, Xie P, Janowiak J, Rudolf B, Schneider U, Curtis S, Bolvin D, Gruber A, Susskind J, Arkin P, Nelkin E. 2003. The version-2 global precipitation climatology project (GPCP) monthly precipitation analysis (1979-present). *Journal of Hydrometeorology* **4**: 1147–1167.

Adler RF, Huffman J, Keehn PR. 1994. Global tropical rain estimates from microwave-adjusted geosynchronous IR data. *Remote Sensing Reviews* **11**: 125–152.

Adler RF, Mack RA. 1984. Thunderstorm cloud height rainfall rate relations for use with satellite rainfall estimation techniques. *Journal of Climate and Applied Meteorology* **23**: 280–296.

Adler RF, Negri AJ. 1988. A satellite technique to estimate tropical convective and stratiform rainfall. *Journal of Applied Meteorology* **27**: 30–51.

Adler RF, Negri AJ, Keehn PR, Hakkarinen IM. 1993. Estimation of monthly rainfall over Japan and surrounding waters from a combination of low orbit microwave and geosynchronous IR data. *Journal of Applied Meteorology* **32**: 335–356.

Ahmad Z, DeLand MT, Cebula RP, Weiss H, Wellemeyer CG, Planet WG, Lienesch JH, Bowman HD, Miller AJ, Nagatani RM. 1994. Accuracy of total ozone retrieval from NOAA SBUV/2measurements: impact of instrument performance. *Journal of Geophysical Research* **99**: 22975–22984.

Albert P, Bennartz R, Preusker R, Leinweber R, Fischer J. 2005. Remote sensing of atmospheric water vapor using the Moderate Resolution Imaging Spectroradiometer. *Journal of Atmospheric and Oceanic Technology* **22**: 309–314.

Allison LJ, Steranka J, Cherrix GT, Hilsenrath E. 1972. Meteorological applications of the Nimbus 4 Temperature-Humidity Infrared Radiometer, 6.7 micron channel data. *Bulletin of the American Meteorological Society* **53**: 526–535.

Amato U, Antoniadis A, Cuomo V, Cutillo L, Franzese M, Murino L, Serio C. 2008. Statistical cloud detection from SEVIRI multispectral images. *Remote Sensing of Environment* **112**: 750–766.

Amato U, Antoniadis A, De Feis I, Masiello G, Matricardi M, Serio C. 2009. Functional sliced inverse regression to infer temperature, water vapour and ozone from IASI data. *Atmospheric Chemistry and Physics* **9**: 5321–5330.

Amorati R, Alberoni PP, Levizzani V, Nanni S. 2000. IR based satellite and radar rainfall estimates of convective storms over Northern Italy. *Meteorological Applications* **7**: 1–18.

Anagnostou EN. 2004. Overview of overland satellite rainfall estimation for hydro-meteorological applications. *Surveys in Geophysics* **25**: 511–537.

Anton M, Cachorro VE, Vilaplana JM, Toledano C, Krotkov NA, Arola A, Serrano A, de la Morena B. 2010. Comparison of UV irradiances from Aura/Ozone Monitoring Instrument (OMI) with Brewer measurements at El Arenosillo (Spain)-Part 1: analysis of parameter influence. *Atmospheric Chemistry and Physics* **10**: 5979–5989.

Anton M, Loyola D, Lopez M, Vilaplana JM, Banon M, Zimmer W, Serrano A. 2009. Comparison of GOME-2/MetOp total ozone data with Brewer spectroradiometer data over the Iberian Peninsula. *Annales Geophysicae* **27**: 1377–1386.

Arkin PA, Meisner BN. 1987. The relationship between large-scale convective rainfall and cold cloud over the western hemisphere during 1982–1984. *Monthly Weather Review* **115**: 51–74.

Arking A, Childs JD. 1985. Retrieval of cloud cover parameters from multispectral satellite images. *Journal of Applied Meteorology* **24**: 322–333.

Ashcroft P, Wentz FJ. 2000. *AMSR algorithm theoretical basis document*. RSS Technical Report 121599B-1. Remote Sensing Systems: Santa Rosa, CA; 27 pp.

Atlas R, Hoffman RN, Leidner SM, Sienkiewicz J, Yu FW, Bloom SC, Brin E, Ardizzone J, Terry J, Bungato D, Jusem JC. 2001. The effects of marine winds from scatterometer data on weather analysis and forecasting. *Bulletin of the American Meteorological Society* **82**: 1965–1990.

Attema EPW. 1991. The active microwave instrument on-board the ERS-1 satellite. *Proceedings of the IEEE* **79**: 791–799.

Aumann HH, Chahine MT, Gautier C, Goldberg MD, Kalnay E, McMillin LM, Revercomb H, Rosenkranz PW, Smith WL, Staelin DH, Strow LL, Susskind J. 2003. AIRS/AMSU/HSB on the aqua mission: design, science objectives, data products, and processing systems. *IEEE Transactions on Geoscience and Remote Sensing* **41**: 253–264.

Ba MB, Ellingson RG, Gruber A. 2003. Validation of a technique for estimating OLR with the GOES sounder. *Journal of Atmospheric and Oceanic Technology* **20**: 79–89.

Ba MB, Gruber A. 2001. GOES multispectral rainfall algorithm (GMSRA). *Journal of Applied Meteorology* **40**: 1500–1514.

Ba MB, Nicholson SE. 1998. Analysis of convective activity and its relationship to the rainfall over the Rift Valley lakes of East Africa during 1983-90 using the Meteosat infrared channel. *Journal of Applied Meteorology* **37**: 1250–1264.

Balaji C, Deiveegan M, Venkateshan SP, Gairola RM, Sarkar A, Agarwal VK. 2009. Polarized microwave forward model simulations for tropical storm Fanoos. *Journal of Earth System Science* **118**: 331–343.

Bankert RL, Mitrescu C, Miller SD, Wade RH. 2009. Comparison of GOES cloud classification algorithms employing explicit and implicit physics. *Journal of Applied Meteorology and Climatology* **48**: 1411–1421.

Bankert RL, Wade RH. 2007. Optimization of an instance-based GOES cloud classification algorithm. *Journal of Applied Meteorology and Climatology* **46**: 36–49.

Baran AJ, Foot JS, Dibben PC. 1993. Satellite detection of volcanic sulphuric acid aerosol. *Geophysical Research Letters* **20**: 1799–1801.

Barkley MP, Monks PS, Hewitt AJ, Machida T, Desai A, Vinnichenko N, Nakazawa T, Yu Arshinov M, Fedoseev N, Watai T. 2007. Assessing the near surface sensitivity of SCIAMACHY atmospheric CO2 retrieved using (FSI) WFM-DOAS. *Atmospheric Chemistry and Physics* **7**: 3597–3619.

Barkstrom BR, Harrison EF, Smith GL, Green RN, Kibler JF, Cess R, The ERBE Science Team. 1989. Earth Radiation Budget Experiment

(ERBE) archival and April 1985 results. *Bulletin of the American Meteorological Society* **70**: 1254–1262.

Barkstrom BR, Smith GL. 1986. The Earth radiation budget experiment, science and implementation. *Review of Geophysics* **24**: 379–390.

Barrett EC, Martin DW. 1981. *The Use of Satellite Data in Rainfall Monitoring*. Academic Press: Riverport.

Barton IJ. 1995. Satellite-derived sea surface temperatures: current status. *Journal of Geophysical Research* **100**: 8777–8790.

Bates TS, Anderson TL, Baynard T, Bond T, Boucher O, Carmichael G, Clarke A, Erlick C, Guo H, Horowitz L, Howell S, Kulkarni S, Maring H, McComiskey A, Middlebrook A, Noone K, O'Dowd CD, Ogren J, Penner J, Quinn PK, Ravishankara AR, Savoie DL, Schwartz SE, Shinozuka Y, Tang Y, Weber RJ, Wu Y. 2006. Aerosol direct radiative effects over the northwest Atlantic, northwest Pacific, and North Indian Oceans: estimates based on in-situ chemical and optical measurements and chemical transport modeling. *Atmospheric Chemistry and Physics* **6**: 1657–732.

Bauer P. 2001. Over-ocean rainfall retrieval from multisensory data or the Tropical Rainfall Measuring Mission. Part I: design and evaluation of inversion databases. *Journal of Atmospheric and Oceanic Technology* **18**: 1315–1330.

Bauer P, Amayenc P, Kummerow CD, Smith EA. 2001. Over-ocean rainfall retrieval from multisensory data or the tropical rainfall measuring mission. Part II: algorithm implementation. *Journal of Atmospheric and Oceanic Technology* **18**: 1838–1855.

Bauer P, Schluessel P. 1993. Rainfall, total water, ice water, and water vapor over sea from polarized microwave simulations and special sensor microwave/imager data. *Journal of Geophysical Research* **98**: 20737–20778.

Baum BA, Arduini RF, Wielicki BA, Minnis P, Tsay SC. 1994. Multilevel cloud retrieval using multispectral HIRS and AVHRR data: nighttime oceanic analysis. *Journal of Geophysical Research* **99**: 5499–5514.

Baum BA, Frey RA, Mace GG, Harkey MK, Yang P. 2003. Nighttime multilayered cloud detection using MODIS and ARM data. *Journal of Applied Meteorology* **42**: 905–919.

Baum BA, Soulen PF, Strabala KI, King MD, Ackerman SA, Menzel WP, Yang P. 2000. Remote sensing of cloud properties using MODIS airborne simulator imagery during SUCCESS 2. Cloud thermodynamic phase. *Journal of Geophysical Research* **105**: 11781–11792.

Baum BA, Tovinkere V, Titlow J, Welch R. 1997. Automated cloud classification of global AVHRR data using a fuzzy logic approach. *Journal of Applied Meteorology* **36**: 1519–1535.

Beer R. 2006. TES on the Aura mission: scientific objectives, measurements, and analysis overview. *IEEE Transactions on Geoscience and Remote Sensing* **44**: 1102–1105.

Beirle S, Kühl S, Pukite J, Wagner T. 2010. Retrieval of tropospheric column densities of NO2 from combined SCIAMACHY nadir/limb measurements. *Atmospheric Measurement Techniques* **3**: 283–299.

Beirle S, Platt U, Wenig M, Wagner T. 2004. Highly resolved global distribution of tropospheric NO2 using GOME narrow swath mode data. *Atmospheric Chemistry and Physics* **4**: 1913–1924.

Bellerby TJ. 2004. A feature-based approach to satellite precipitation monitoring using geostationary IR imagery. *Journal of Hydrometeorology* **5**: 910–921.

Bellerby T, Hsu K, Sorooshian S. 2009. LMODEL: a satellite precipitation methodology using cloud development modeling. Part I: Algorithm construction and calibration. *Journal of Hydrometeorology* **10**: 1081–1095.

Bellon A, Lovejoy S, Austin GL. 1980. Combining satellite and radar data for the short-range forecasting of precipitation. *Monthly Weather Review* **108**: 1554–1556.

Bendix J. 1997. Adjustment of the convective-stratiform technique (CST) to estimate 1991/93 El Nino rainfall distribution in Ecuador and Peru by means of Meteosat-3 data. *International Journal of Remote Sensing* **18**: 1387–1394.

Bendix J. 2000. Precipitation dynamics in Ecuador and Northern Peru during the 1991/92 El Nino: a remote sensing perspective. *International Journal of Remote Sensing* **21**: 533–548.

Bendix J. 2002. A satellite-based climatology of fog and low-level stratus in Germany and adjacent areas. *Atmospheric Research* **64**: 3–18.

Bendix J, Bachmann M. 1991. Ein operationell einsetzbares Verfahren zur Nebelerkennung auf der Basis von AVHRR-Daten der NOAA-Satelliten. *Meteorologische Rundschau* **43**: 169–178.

Bendix J, Rollenbeck R, Palacios WE. 2004. Cloud detection in the Tropics-a suitable tool for climate-ecological studies in the high mountains of Ecuador. *International Journal of Remote Sensing* **25**: 4521–4540.

Bendix J, Thies B, Cermak J, Nauß T. 2005. Ground fog detection scheme from space based on MODIS daytime data-a feasibility study. *Weather and Forecasting* **20**: 989–1005.

Bendix J, Thies B, Nauss T, Cermak J. 2006. A feasibility study of daytime fog and low stratus detection with TERRA/AQUA-MODIS over land. *Meteorological Applications* **13**: 111–125.

Bennartz R, Fischer J. 2001. Retrieval of columnar water vapour over land from backscattered solar radiation using the medium resolution imaging spectrometer. *Remote Sensing of Environment* **78**: 274–283.

Bennartz R, Thoss A, Dybbroe A, Michelson DB. 2002. Precipitation analysis using the advanced microwave sounding unit in support of nowcasting applications. *Meteorological Applications* **9**: 177–189.

Berendes TA, Kuo KS, Logar AM, Corwin EM, Welch RM, Baum BA, Pretre A, Wege RC. 1999. A comparison of paired histogram, maximum likelihood, class elimination, and neural network approaches for daylight global cloud classification using AVHRR imagery. *Journal of Geophysical Research* **104**: 6199–6213.

Berendes TA, Mecikalski JR, MacKenzie WM Jr, Bedka KM, Nair US. 2009. Convective cloud identification and classification in daytime satellite imagery using standard deviation limited adaptive clustering. *Journal of Geophysical Research* **113**: D20207.

Berg W, L'Ecuyer T, Haynes JM. 2010. The distribution of rainfall over oceans from spaceborne radars. *Journal of Applied Meteorology and Climatology* **49**: 535–543.

Bernath PF, McElroy CT, Abrams MC, Boone CD, Butler M, Camy-Peyret C, Carleer M, Clerbaux C, Coheur PF, Colin R, DeCola P, DeMazière M, Drummond JR, Dufour D, Evans WFJ, Fast H, Fussen D, Gilbert K, Jennings DE, Llewellyn EJ, Lowe RP, Mahieu E, McConnell JC, McHugh M, McLeod SD, Michaud R, Midwinter C, Nassar R, Nichitiu F, Nowlan C, Rinsland CP, Rochon YJ, Rowlands N, Semeniuk K, Simon P, Skelton R, Sloan JJ, Soucy MA, Strong K, Tremblay P, Turnbull D, Walker KA, Walkty I, Wardle DA, Wehrle V, Zander R, Zou J. 2005. Atmospheric chemistry experiment (ACE): mission overview. *Geophysical Research Letters* **32**: L15S01.

Bertaux JL, Hauchecorne A, Dalaudier F, Cot C, Kyrölä E, Fussen D, Tamminen J, Leppelmeier GW, Sofieva V, Hassinen S, d'Andon OF, Barrot G, Mangin A, Theodore B, Guirlet M, Korablev O, Snoeij P, Koopman R, Fraisse R. 2004. First results on GOMOS/Envisat. *Advances in Space Research* **33**: 1029–1035.

Bertaux JL, Kyrölä E, Fussen D, Hauchecorne A, Dalaudier F, Sofieva V, Tamminen J, Vanhellemont F, Fanton d'Andon O, Barrot G, Mangin A, Blanot L, Lebrun JC, Perot K, Fehr T, Saavedra L, Fraisse R. 2010. Global ozone monitoring by occultation of stars: an overview of GOMOS measurements on ENVISAT. *Atmospheric Chemistry and Physics Discussions* **10**: 9917–10076.

Bettenhausen MH, Smith CK, Bevilacqua RM, Wang N, Gaiser PW. 2006. A nonlinear optimization algorithm for WindSat wind vector retrievals. *IEEE Transactions on Geoscience and Remote Sensing* **44**: 597–609.

Bezy JL, Leibrandt W, Heliere A, Silvestrin P, Lin CC, Ingmann P, Kimura T, Kumagai H. 2005. The ESA Earth Explorer EarthCARE mission. *Proceedings of SPIE* **5882**: 58820F.

Bhartia PK, McPeters RD, Mateer CL, Flynn LE, Wellemeyer C. 1996. Algorithm for the estimation of vertical ozone profiles from the backscattered ultraviolet technique. *Journal of Geophysical Research* **101**: 18793–18806.

Bidwell SW. 2005. The Global Precipitation Measurement (GPM) Microwave Imager (GMI) instrument: role, performance, and status. *Proceedings of IGARSS 2005*, Seoul, Korea, 25–29 July 2005. IEEE: Piscataway, NJ; 1–4.

Birkenheuer D, Gutman S. 2005. A comparison of GOES moisture-derived product and GPS-IPW data during IHOP-2002. *Journal of Atmospheric and Oceanic Technology* **22**: 1838–1845.

Bloom HJ. 2001. The Cross-track Infrared Sounder (CrIS): a sensor for operational meteorological remote sensing. *Proceedings of Geoscience and Remote Sensing Symposium IGARSS*, Sydney, AUS, 9–13 July 2001. IEEE: Piscataway, NJ; 1341–1343.

Blumstein D, Chalon G, Carlier T, Buil C, Hébert P, Maciaszek T, Ponce G, Phulpin T, Tournier B, Simeoni D. 2004. IASI instrument: technical overview and measured performances. *Proceedings of SPIE Conference on Infrared Spaceborne Remote Sensing*, Denver, CO, 2 August 2004. SPIE: Bellingham, WA DOI: 10.1117/12.560907.

Bluth GJS, Dorion SD, Schnetzler CC, Krueger AJ, Walter LS. 1992. Global tracking of the SO clouds from the Mount Pinatubo eruptions. *Geophysical Research Letters* **19**: 151–154.

Bluth GJS, Dorion SD, Schnetzler CC, Krueger AJ, Walter LS. 1993. The contribution of explosive volcanism to global atmospheric sulfur dioxide concentrations. *Nature* **366**: 327–329.

Boersma KF, Bucsela EJ, Brinksma EJ, Gleason JF. 2002. In *NO2, in OMI Algorithm Theoretical Basis Document, OMI Trace Gas Algorithms, ATB OMI-04, Version 2.0*, Chance K (ed.), Vol. 4. NASA Distributed Active Archive Centers: Greenbelt, MD.

Boersma KF, Eskes HJ, Brinksma EJ. 2004. Error analysis for tropospheric NO2 retrieval from space. *Journal of Geophysical Research* **109**: D04311.

Boersma KF, Eskes HJ, Veefkind JP, Brinksma EJ, van der ARJ, Sneep M, van den Oord GHJ, Levelt PF, Stammes P, Gleason JF, Bucsela EJ. 2007. Near-real time retrieval of tropospheric NO2 from OMI. *Atmospheric Chemistry and Physics* **7**: 2103–2118.

Bovensmann H, Burrows JP, Buchwitz M, Frerick J, Noël S, Rozanov VV, Chance KV, Goede APH. 1999. SCIAMACHY: mission objectives and measurement modes. *Journal of the Atmospheric Sciences* **56**: 127–150.

Bowen GJ, Revenaugh J. 2003. Interpolating the isotopologic composition of modern meteoric precipitation. *Water Resources Research* **39**: 1299.

Boynard A, Clerbaux C, Coheur PF, Hurtmans D, Turquety S, George M, Hadji-Lazaro J, Keim C, Mayer-Arnek J. 2009. Measurements of total and tropospheric ozone from the IASI instrument: comparison with satellite and ozonesonde observations. *Atmospheric Chemistry and Physics* **9**: 6255–6271.

Breon FM, Colzy S. 2000. Global distribution of cloud droplet effective radius from POLDER polarization measurements. *Geophysical Research Letters* **27**: 4065–4068.

Brindley H, Ignatov A. 2006. Retrieval of mineral aerosol optical depth and size information from Meteosat second generation SEVIRI solar reflectance bands. *Remote Sensing of Environment* **102**: 344–363.

Brueske KF, Velden CS. 2003. Satellite-based tropical cyclone intensity estimation using the NOAA-KLM series Advanced Microwave Sounding Unit (AMSU). *Monthly Weather Review* **131**: 687–697.

Buchwitz M, de Beek R, Burrows JP, Bovensmann H, Warneke T, Notholt J, Meirink JF, Goede APH, Bergamaschi P, Körner S, Heimann M, Schulz A. 2005a. Atmospheric methane and carbon dioxide from SCIAMACHY satellite data: initial comparison with global models of chemistry and transport. *Atmospheric Chemistry and Physics* **5**: 941–962.

Buchwitz M, de Beek R, Noel S, Burrows JP, Bovensmann H, Bremer H, Bergamaschi P, Körner S, Heimann M. 2005b. Carbon monoxide, methane and carbon dioxide columns retrieved from SCIAMACHY by WFM-DOAS: year 2003 initial data set. *Atmospheric Chemistry and Physics* **5**: 3313–3329.

Buchwitz M, de Beek R, Noel S, Burrows JP, Bovensmann H, Schneising O, Khlystova I, Bruns M, Bremer H, Bergamaschi P, Körner S, Heimann M. 2006. Atmospheric carbon gases retrieved from SCIAMACHY by WFM-DOAS: version 0.5 CO and CH4 and impact of calibration improvements on CO2 retrieval. *Atmospheric Chemistry and Physics* **6**: 2727–2751.

Buchwitz M, Noël S, Bramstedt K, Rozanov VV, Eisinger M, Bovensmann H, Tsvetkova S, Burrows JP. 2004. Retrieval of trace gas vertical columns from SCIAMACHY/ENVISAT near-infrared nadir spectra: first preliminary results. *Advances in Space Research* **34**: 809–814.

Bucsela EJ, Celarier EA, Wenig MO, Gleason JF, Veefkind JP, Boersma KF, Brinksma EJ. 2006. Algorithm for NO2 vertical column retrieval from the ozone monitoring instrument. *IEEE Transactions on Geoscience and Remote Sensing* **44**: 1245–1258.

Burrows J, Weber M, Buchwitz M, Rozanov VV, Ladstädter-Weissenmayer A, Richter A, de Beek R, Hoogen R, Bramstedt K, Eichmann KU, Eisinger M, Perner D. 1999. The global ozone monitoring experiment (GOME): mission concept and first scientific results. *Journal of Atmospheric Science* **56**: 151–175.

Callies J, Corpaccioli E, Eisinger M, Hahne A, Lefebvre A. 2000. GOME-2: Metop's second generation sensor for operational ozone monitoring. *ESA Bulletin* **102**: 28–36.

Capacci D, Porcu F. 2009. Evaluation of a satellite multispectral VIS-IR daytime statistical rain-rate classifier and comparison with passive microwave rainfall estimates. *Journal of Applied Meteorology and Climatology* **48**: 284–300.

Cardone V, Chester T, Lipes R. 1983. Evaluation of Seasat SMMR wind speed measurements. *Journal of Geophysical Research* **88**: 1709–1726.

Carmo JB, Keller M, Dias JD, de Camargo PD, Crill P. 2006. A source of methane from upland forests in the Brazilian Amazon. *Geophysical Research Letters* **33**: L04809.

Carn SA, Krotkov NA, Gray MA, Krueger AJ. 2004. Fire at Iraqi sulfur plant emits SO2 clouds detected by Earth Probe TOMS. *Geophysical Research Letters* **31**: L19105.

Carn SA, Krueger AJ, Bluth GJS, Schaefer SJ, Krotkov NA, Watson IM, Datta S. 2003. Volcanic eruption detection by the Total Ozone Mapping Spectrometer (TOMS) instruments: a 22-year record of sulphur dioxide and ash emissions. In *Volcanic Degassing*, Special Publication. Oppenheimer C, Pyle DM, Barclay J (eds). Geological Society: London; 177–202.

Carn SA, Krueger AJ, Krotkov NA, Yang K, Levelt PF. 2007. Sulfur dioxide emissions from Peruvian copper smelters detected by the ozone monitoring instrument. *Geophysical Research Letters* **34**: L09801.

Carn SA, Strow LL, de Souza-Machado S, Edmonds Y, Hannon S. 2005. Quantifying tropospheric volcanic emissions with Airs: the 2002 eruption of Mt. Etna (Italy). *Geophysical Research Letters* **32**: L02301.

Casadio S, Zehner C, Pisacane G, Putz E. 2000. Empirical retrieval of the atmospheric air mass factor (ERA) for the measurement of water vapour vertical content using GOME data. *Geophysical Research Letters* **27**: 1483–1486.

Celarier EA, Brinksma EJ, Gleason JF, Veefkind JP, Cede A, Herman JR, Ionov D, Goutail F, Pommereau JP, Lambert JC, van Roozendel M., Pinardi G, Wittrock F, Schönhardt A, Richter A, Ibrahim OW, Wagner T, Bojkov B, Mount G, Spinei E, Chen CM, Pougetti TJ, Sander SP, Bucsela EJ, Wenig MO, Swart DPJ, Volten H, Kroon M, Levelt PF. 2008. Validation of Ozone Monitoring Instrument nitrogen dioxide columns. *J. Geophys. Res.* **113**: D15S15.

Cermak J, Bendix J. 2007. Dynamical Night time Fog/Low Stratus Detection Based on Meteosat SEVIRI Data: A Feasibility Study. *Pure Appl. Geophys.* **164**: 1179–1192.

Cermak J, Bendix J. 2008. A novel approach to fog/low stratus detection using Meteosat 8 data. *Atmospheric Research* **87**: 279–292.

Cermak J, Bendix J. 2011. Detecting ground fog from space-a microphysics-based approach. *International Journal of Remote Sensing* **32**: 3345–3371.

Chaboureau JP, Chédin A, Scott N. 1998. Remote sensing of the vertical distribution of atmospheric water vapor from the TOVS observations: method and validation. *Journal of Geophysical Research* **103**: 8743–8752.

Chae JH, Sherwood SC. 2010. Insights into cloud-top height and dynamics from the seasonal cycle of cloud-top heights observed by MISR in the West Pacific region. *Journal of the Atmospheric Sciences* **67**: 248–261.

Chahine MT, Pagano TS, Aumann HH, Atlas R, Barnet C, Blaisdell J, Chen L, Divakarla M, Fetzer EJ, Goldberg M, Gautier C, Granger S, Hannon S, Irion FW, Kakar R, Kalnay E, Lambrigtsen BH, Lee SY, Le Marshall J, McMillan WW, McMillin L, Olsen ET, Revercomb H, Rosenkranz P, Smith WL, Staelin D, Larrabee Strow L, Susskind J, Tobin D, Wolf W, Zhou L. 2006. AIRS: improving weather forecasting and providing new data on greenhouse gases. *Bulletin of the American Meteorological Society* **87**: 911–26.

Chance K. 1998. Analysis of BrO measurements from the global ozone monitoring experiment. *Geophysical Research Letters* **25**: 3335–3338.

Chance KV, Burrows JP, Perner D, Schneider W. 1997. Satellite measurements of atmospheric ozone profiles, including tropospheric ozone, from ultraviolet/visible measurements in the nadir geometry: a potential method to retrieve tropospheric ozone. *Journal of Quantitative Spectroscopy and Radiative Transfer* **57**: 467–476.

Chance KV, Burrows JP, Schneider W. 1991. Retrieval and molecule sensitivity studies for the global ozone monitoring experiment and the scanning imaging absorption spectrometer for atmospheric chartography. *Proceedings of the Society of Photo-Optical Instrumentation Engineers* **1491**: 151–165.

Chand D, Anderson TL, Wood R, Charlson RJ, Hu Y, Liu Z, Vaughan M. 2008. Quantifying above-cloud aerosol using space-borne lidar for improved understanding of cloudy-sky direct climate forcing. *Journal of Geophysical Research* **113**: D13206.

Chang FL, Li Z. 2002. Estimating the vertical variation of cloud droplet effective radius using multispectral near-infrared satellite measurements. *Journal of Geophysical Research* **107**(D15): 1–12.

Chang FL, Li Z. 2003. Retrieving vertical profiles of water-cloud droplet effective radius: Algorithm modification and preliminary application. *Journal of Geophysical Research* **108**(D24): 4763.

Chang FL, Minnis P, Lin B, Khaiyer MM, Palikonda R, Spangenberg DA. 2010. A modified method for inferring upper troposphere cloud top height using the GOES 12 imager 10.7 and 13.3 μm data. *Journal of Geophysical Research* **115**: D06208.

Charlock TP, Rose FG, Rutan DA, Alberta TL, Kratz DP, Coleman LH, Smith GL, Manalo-Smith N, Bess TD. 1997. *Compute Surface and Atmospheric Fluxes (System 5.0)*, CERES Algorithm Theoretical Basis Document. NASA Langley Research Center: Hampton, VA; 84 pp.

Chelton DB, Freilich MH. 2005. Scatterometer-based assessment of 10-m wind analysis from the operational ECMWF and NCEP numerical weather prediction models. *Monthly Weather Review* **133**: 409–29.

Chelton DB, Freilich MH, Sienkiewicz JM, Von Ahn JM. 2006. On the use of QuikSCAT scatterometer measurements of surface winds for marine weather prediction. *Monthly Weather Review* **134**: 2055–2071.

Chelton DB, Wentz FJ. 2005. Global microwave satellite observations of sea surface temperature for numerical weather prediction and climate research. *Bulletin of the American Meteorological Society* **86**: 1097–1115.

Chen FW, Staelin DH. 2003. AIRS/AMSU/HSB precipitation estimates. *IEEE Transactions on Geoscience and Remote Sensing* **41**: 410–417.

Cheng M, Brown R. 1995. Delineation of precipitation areas by correlation of Meteosat visible and infrared data with radar data. *Monthly Weather Review* **123**: 2743–2757.

Cheng M, Brown R, Collier CG. 1993. Delineation of precipitation areas by correlation of METEOSAT visible and infrared data in the region of the United Kingdom. *Journal of Applied Meteorology* **32**: 884–898.

Chepfer H, Brogniez G, Fouquart Y. 1998. Cirrus clouds microphysical properties deduced from POLDER observations. *Journal of Quantitative Spectroscopy and Radiative Transfer* **60**: 375–390.

Chepfer H, Brogniez G, Goloub P, Breon FM, Flamant PH. 1999. Cirrus cloud ice crystals horizontally oriented in space observed with POLDER/ADEOS. *Journal of Quantitative Spectroscopy and Radiative Transfer* **63**: 521–543.

Cheruy F, Kandel RS, Duvel JP. 1991. Outgoing long wave radiation and its diurnal variation from combined ERBE and METEOSAT observations. Part II: Using METEOSAT data to determine the LW diurnal cycle. *Journal of Geophysical Research* **96**: 22623–22630.

Christian HJ, Blakeslee RJ, Goodman SJ. 1992. *Lightning Imaging Sensor (LIS) for the Earth Observing System*, NASA Technological Memorandum 4350. Center for Aerospace Information: Baltimore, MD; 36 pp.

Chung ES, Soden BJ. 2010. Investigating the influence of carbon dioxide and the stratosphere on the long-term tropospheric temperature monitoring from HIRS. *Journal of Applied Meteorology and Climatology* **49**: 1927–1937.

Cinzano P, Falchi F, Elvidge CD, Baugh KE. 2000. The artificial night sky brightness mapped from DMSP satellite operational linescan system measurements. *Monthly Notices of the Royal Astronomical Society* **318**: 641–657.

Clarisse L, Coheur PF, Prata AJ, Hurtmans D, Razavi A, Hadji-Lazaro J, Clerbaux C, Phulpin T. 2008. Tracking and quantifying volcanic SO2 with IASI, the September 2007 eruption at Jebel-at-Tair. *Atmospheric Chemistry and Physics* **8**: 7723–7734.

Clarisse L, Prata F, Lacour J-L, Hurtmans D, Clerbaux C, Coheur P-F. 2010a. A correlation method for volcanic ash detection using hyperspectral infrared measurements. *Geophysical Research Letters* **37**: L19806.

Clarisse L, Hurtmans D, Prata AJ, Karagulian F, Clerbaux C, De Maziére M, Coheur P-F. 2010b. Retrieving radius, concentration, optical depth, and mass of different types of aerosols from high-resolution infrared nadir spectra. *Applied Optics* **49**: 3713–3722.

Clerbaux N, Dewitte S, Bertrand C, Caprion D, De Paepe B, Gonzalez L, Ipe A. 2008. Unfiltering of the Geostationary Earth Radiation Budget (GERB) data. Part I: short wave radiation. *Journal of Atmospheric and Oceanic Technology* **25**: 1087–1105.

Coakley JA, Bretherton FP. 1982. Cloud cover from high-resolution scanner data: detecting and allowing for partially filled fields of view. *Journal of Geophysical Research* **87**: 4917–4932.

Coll C, Wan Z, Galve JM. 2009. Temperature-based and radiance-based validations of the V5 MODIS land surface temperature product. *Journal of Geophysical Research* **114**: D20102.

Connor LN, Chang PS, Jelenak Z, Wang NY, Mavor TP. 2004. *WindSat validation datasets: an overview*. Proceedings IGARSS, vol. 1, September 2004, Anchorage; 386–389.

Coppo P, Ricciarelli B, Brandani F, Delderfield J, Ferlet M, Mutlow C, Munro G, Nightingale T, Smith D, Bianchi S, Nicol P, Kirschstein S, Hennig T, Engel W, Frerick J, Nieke J. 2010. SLSTR: a high accuracy dual scan temperature radiometer for sea and land surface monitoring from space. *Journal of Modern Optics* **57**: 1815–91830.

Coppola E, Grimes DIF, Verdecchia M, Visconti G. 2006. Validation of improved TAMANN neural network for operational satellite-derived rainfall estimation in Africa. *Journal of Applied Meteorology and Climatology* **45**: 1557–1572.

Corlett GK, Barton IJ, Donlon CJ, Edwards MC, Good SA, Horrocks LA, Llewellyn-Jones DT, Merchant CJ, Minnett PJ, Nightingale TJ, Noyes EJ, O'Carroll AG, Remedios JJ, Robinson IS, Saunders RW, Watts JG. 2006. The accuracy of SST retrievals from AATSR: an initial assessment through geophysical validation against in situ radiometers, buoys and other SST data sets. *Advances in Space Research* **37**: 764–69.

Crevoisier C, Chedin A, Matsueda H, Machida T, Armante R, Scott NA. 2009a. First year of upper tropospheric integrated content of CO2 from IASI hyperspectral infrared observations. *Atmospheric Chemistry and Physics* **9**: 4797–4810.

Crevoisier C, Nobileau D, Fiore AM, Armante R, Chedin A, Scott NA. 2009b. Tropospheric methane in the tropics-first year from IASI hyperspectral infrared observations. *Atmospheric Chemistry and Physics* **9**: 6337–6350.

Crevoisier C, Chedin A, Scott NA. 2003. AIRS channel selection for CO2 and other trace-gas retrievals. *Quarterly Journal of the Royal Meteorological Society* **129**: 2719–2740.

Crevoisier C, Heilliette S, Chédin A, Serrar S, Armante R, Scott NA. 2004. Midtropospheric CO2 concentration retrieval from AIRS observations in the tropics. *Geophysical Research Letters* **31**: L17106.

Deb SK, Kishtawal CM, Pal PK. 2010. Impact of Kalpana-1-derived water vapor winds on Indian Ocean Tropical cyclone forecasts. *Monthly Weather Review* **138**: 987–1003.

Deeter MN. 2007. A new satellite retrieval method for precipitable water vapor over land and ocean. *Geophysical Research Letters* **34**: L02815.

Deeter MN, Edwards DP, Gille JC. 2007. Retrievals of carbon monoxide profiles from MOPITT observations using lognormal a priori statistics. *Journal of Geophysical Research* **112**: D11311.

Deeter MN, Emmons LK, Francis GL, Edwards DP, Gille JC, Warner JX, Khattatov B, Ziskin D, Lamarque JF, Ho SP, Yudin V, Attie JL, Packman D, Chen J, Mao D, Drummond JR. 2003. Operational carbon monoxide retrieval algorithm and selected results for the MOPITT instrument. *Journal of Geophysical Research* **108**(D14): 4399.

Deeter MN, Emmons LK, Francis GL, Edwards DP, Gille JC, Warner JX, Khattatov B, Ziskin D, Lamarque JF, Ho SP, Yudin V, Attie JL, Packman D, Chen J, Mao D, Drummond JR, Novelli P, Sachse G. 2004. Evaluation of operational radiances for the Measurements of Pollution in the Troposphere (MOPITT) instrument CO thermal band channels. *Journal of Geophysical Research* **109**: D03308.

De Maziere M, Vigouroux C, Bernath PF, Baron P, Blumenstock T, Boone C, Brogniez C, Catoire V, Coffey M, Duchatelet P, Griffith D, Hannigan J, Kasai Y, Kramer I, Jones N, Mahieu E, Manney GL, Piccolo C, Randall C, Robert C, Senten C, Strong K, Taylor J, Tétard C, Walker KA, Wood S. 2008. Validation of ACE-FTS v2.2 methane profiles from the upper troposphere to the lower mesosphere. *Atmospheric Chemistry and Physics* **8**: 2421–2435.

Demuth JL, DeMaria M, Knaff JA, Vonder Haar TH. 2004. Evaluation of advanced microwave sounding unit tropical-cyclone intensity and size estimation algorithms. *Journal of Applied Meteorology* **43**: 282–296.

Derrien M, Farki B, Harang L, Le Gleau H, Noyalet A, Pochic D, Sairouni A. 1993. Automatic cloud detection applied to NOAA-11/AVHRR imagery. *Remote Sensing of Environment* **46**: 246–267.

Derrien M, Le Gléau H. 2005. MSG/SEVIRI cloud mask and type from SAFNWC. *International Journal of Remote Sensing* **26**: 4707–4732.

Derrien M, Le Gleau H. 2010. Improvement of cloud detection near sunrise and sunset by temporal-differencing and region-growing techniques with real time SEVIRI. *International Journal of Remote Sensing* **31**: 1765–1780.

Desbois M, Seze G, Szejwach G. 1982. Automatic classification of clouds on METEOSAT imagery: application to high level clouds. *Journal of Applied Meteorology* **21**: 401–412.

Deschamps PY, Bréon FM, Leroy M, Podaire A, Bricaud A, Buriez JC, Sèze G. 1994. The POLDER mission: instrument characteristics and scientific objectives. *IEEE Transactions on Geoscience and Remote Sensing* **32**: 598–615.

Deuze JL, Breon FM, Devaux C, Goloub P, Herman M, Lafrance B, Maignan F, Marchand A, Nadal F, Perry G, Tanre D. 2001. Remote sensing of aerosols over land surfaces from POLDER-ADEOS-1 polarized measurements. *Journal of Geophysical Research* **106**: 4913–4926.

Deuze JL, Goloub P, Herman M, Marchand A, Perry G, Susana S, Tanré D. 2000. Estimate of the aerosol properties over the ocean with POLDER. *Journal of Geophysical Research* **105**: 15329–15346.

Deuze JL, Herman M, Goloub P, Tanre D, Marchand A. 1999. Characterization of aerosols over ocean from POLDER/ADEOS-1. *Geophysical Research Letters* **26**: 1421–1424.

Diaz JP, Arbelo M, Expósito FJ, Podestá G, Prosperio JM, Evans R. 2001. Relationship between errors in AVHRR-derived sea surface temperature and the TOMS aerosol index. *Geophysical Research Letters* **28**: 1989–1992.

Dinelli BM, Arnone E, Brizzi G, Carlotti M, Castelli E, Magnani L, Papandrea E, Prevedelli M, Ridolfi M. 2010. The MIPAS2D database of MIPAS/ENVISAT measurements retrieved with a multi-target 2-dimensional tomographic approach. *Atmospheric Measurements Techniques* **3**: 355–374.

Diner DJ, Beckert JC, Bothwell GW, Rodriguez JI. 2002. Performance of the MISR instrument during its first 20 months in Earth orbit. *IEEE Transactions on Geoscience and Remote Sensing* **40**: 1449–1466.

Diner DJ, Beckert JC, Reilly TH, Bruegge CJ, Couel JE, Kahn RA, Martonchik JV, Ackerman TP, Davies R, Gerstl SAW, Gordon HR, Muller JP, Myneni RB, Sellers PJ, Pinty B, Verstaete MM. 1998. Multiangle Imaging Spectroradiometer (MISR) description and experiment overview. *IEEE Transactions on Geoscience and Remote Sensing* **36**: 1072–1087.

Diner DJ, Braswell BH, Davies R, Gobron N, Hu J, Jin Y, Krahn RA, Knyazikhin Y, Loeb N, Muller JP, Nolin AW, Pinty B, Schaaf CB, Seiz G, Stroeve J. 2005. The value of multiangle measurements for retrieving structurally and radiatively consistent properties of clouds, aerosols, and surfaces. *Remote Sensing of Environment* **97**: 495–518.

Diner DJ, Davies R, Di Girolamo L, Horvath A, Moroney C, Muller JP, Paradise SR, Wenkert D, Zong J. 1999. *MISR Level-2 Cloud Detection and Classification Algorithm Theoretical Basis Document*, Technical Document D-11399. JPL: Pasadena, CA; 102.

Dinku T, Anagnostou EN. 2005. Regional differences in overland rainfall estimation from PR-calibrated TMI algorithm. *Journal of Applied Meteorology* **44**: 189–205.

Di Tomaso E, Romano F, Cuomo V. 2009. Rainfall estimation from satellite passive microwave observations in the range 89 GHz to 190 GHz. *Journal of Geophysical Research* **114**: D18203.

Di Vittorio A, Emery W. 2002. An automated, dynamic threshold cloudmasking algorithm for daytime AVHRR images over land. *IEEE Transactions on Geoscience and Remote Sensing* **40**: 1682–1694.

Dong C, Yang J, Zhang W, Yang Z, Lu N, Shi J, Zhang P, Liu Y, Cai B. 2009. An overview of a New Chinese weather satellite FY-3A. *Bulletin of the American Meteorological Society* **90**: 1531–1544.

Draper DW, Long DG. 2004. Simultaneous wind and rain retrieval using seawinds data. *IEEE Transactions on Geoscience and Remote Sensing* **42**: 1411–1423.

Drummond JR. 2002. MOPITT: 12 years of planning and 2.5 years of operations. *Proceedings of IGARSS Geoscience and Remote Sensing Symposium*, Toronto, Canada, 24–28 Jun 2002. IEEE: Piscataway, NJ; 1085–1087.

Dulac F, Tanre D, Bergametti G, Buat-Menard P, Desbois M, Sutton D. 1992. Assessment of the African airborne dust mass over the western mediterranean sea using Meteosat data. *Journal of Geophysical Research* **97**: 2489–2506.

Dunion JP, Velden CS. 2002. Application of surface-adjusted GOES low-level cloud-drift winds in the environment of Atlantic tropical cyclones, Part I: methodology and validation. *Monthly Weather Review* **130**: 1333–1346.

Ebert E, Janowiak J, Kidd C. 2007. Comparison of near-realtime precipitation estimates from satellite observations and numerical models. *Bulletin of the American Meteorological Society* **88**: 47–64.

Eisinger M, Burrows JP. 1998. Tropospheric sulfur dioxide observed by the ERS-2 GOME instrument. *Geophysical Research Letters* **25**: 4177–4180.

Ellingson RG, Yanuk DJ, Lee HT, Gruber A. 1989. A technique for estimating outgoing long wave radiation from HIRS radiance observations. *Journal of Atmospheric and Oceanic Technology* **6**: 706–711.

Ellrod GP. 1995. Advances in the detection and analysis of fog at night using goes multispectral infrared imagery. *Weather and Forecasting* **10**: 606–619.

Elvidge CD, Baugh KE, Dietz JB, Bland T, Sutton PC, Kroehl HW. 1998. Radiance calibration of DMSP-OLS low-light imaging data of human settlements. *Remote Sensing of Environment* **68**: 77–88.

Engelen RJ, Andersson E, Chevallier F, Hollingsworth A, Matricardi M, McNally AP, Thépaut JN, Watts PD. 2004. Estimating atmospheric CO2 from advanced infrared satellite radiances within an operational four-dimensional variational (4DVar) data assimilation system: methodology and first results. *Journal of Geophysical Research* **109**: D19309.

Engelen RJ, Stephens GL. 1999. Characterization of water-vapour retrievals from TOVS/HIRS and SSM/T-2 measurements. *Quarterly Journal of the Royal Meteorological Society* **125**: 331–351.

EUMETSAT. 2011. *Meteosat First Generation User Handbook*, EUM/OPS/USR/10/1537, v1A. EUMETSAT: Darmstadt.

Eymard L, Gheudin M, Laborie P, Sirou F, Le Gac C, Vinson JP, Franquet S, Desbois M, Roca R, Scott N, Waldteufel P. 2001. The SAPHIR humidity sounder. *Proceedings of the MEGHA-TROPIQUES 2nd Scientific Workshop*, Paris, France, 2–6 July 2001. MEGHA-TROPIQUES: Paris/Bangalore.

Eyre JR. 1997. Variational assimilation of remotely-sensed observations of the atmosphere. *Journal of Meteorological Society of Japan* **75**: 331–338.

Eyre JR, Brownscombe JL, Allam RJ. 1984. Detection of fog at night using Advanced Very High Resolution Radiometer (AVHRR) imagery. *Meteorological Magazine* **113**: 266–271.

Faysash DA, Smith EA. 1999. Simultaneous land surface temperature-emissivity retrieval in the infrared split window. *Journal of Atmospheric and Oceanic Technology* **16**: 1673–1689.

Feijt AJ, Jolivet D, Koelemeijer R, Deneke H. 2004. Recent improvements to LWP retrievals from AVHRR. *Atmospheric Research* **72**: 3–15.

Fernandez P. 2004. *Software user manual for the PGE06 of the SAFNWC/MSG: scientific part, SAF/NWC/IOP/INM/SCI/SUM/06*, March 2004.

Ferraro RR. 1997. Special sensor microwave imager derived global rainfall estimates for climatological applications. *Journal of Geophysical Research* **102**: 16715–16735.

Ferraro RR, Marks GF. 1995. The development of SSM/I rain-rate retrieval algorithms using ground-based radar measurements. *Journal of Atmospheric and Oceanic Technology* **12**: 755–770.

Ferraro R, Weng F, Grody NC, Zhao L, Meng H, Kongoli C, Pellegrino P, Qiu S, Dean C. 2005. NOAA operational hydrological products derived from the advanced microwave sounding unit. *IEEE Transactions on Geoscience and Remote Sensing* **43**: 1036–1049.

Ferreira F, Amayenc P, Oury S, Testud J. 2001. Study and test of improved rain estimates from the TRMM precipitation radar. *Journal of Applied Meteorology* **40**: 1878–1899.

Fichaux N, Poglio T, Ranchin T. 2005. Mapping offshore wind resources: synergetic potential of SAR and scatterometer data. *IEEE Journal of Oceanic Engineering* **3**: 516–525.

Figa-Saldaña J, Wilson JJW, Attema E, Gelsthorpe R, Drinkwater MR, Stoffelen A. 2002. The advanced scatterometer (ASCAT) on the meteorological operational (MetOp) platform: a follow on for European wind scatterometers. *Canadian Journal of Remote Sensing* **28**: 404–412.

Fischer H, Birk M, Blom C, Carli B, Carlotti M, von Clarmann T, Delbouille L, Dudhia A, Ehhalt D, Endemann M, Flaud JM, Gessner R, Kleinert A, Koopman R, Langen J, López-Puertas M, Mosner P, Nett H, Oelhaf H, Perron G, Remedios J, Ridolfi M, Stiller G, Zander R. 2008. MIPAS: an instrument for atmospheric and climate research. *Atmospheric Chemistry and Physics* **8**: 2151–2188.

Fischer H, Eigenwillig N, Mueller H. 1981. Information content of Meteosat and Nimbus/THIR water vapor channel data: altitude association of observed phenomena. *Journal of Applied Meteorology* **20**: 1344–1352.

Fischer J, Grassl H. 1991. Detection of cloud-top height from backscattered radiances within the oxygen A band. Part 1: theoretical study. *Journal of Applied Meteorology* **30**: 1245–1259.

Fishman J, Bowman KW, Burrows JP, Richter A, Chance KV, Edwards DP, Martin RV, Morris GA, Pierce RB, Ziemke JR, Al-Saadi JA, Creilson JK, Schaack TK, Thompson AM. 2008. Remote sensing of tropospheric pollution from space. *Bulletin of the American Meteorological Society* **89**: 805–21.

Flaming GM. 2005. Global precipitation measurement update. *Proceedings on IGARSS*, Seoul, Korea, 25–29 July 2005. IEEE: Piscataway, NJ; 1–4.

Flynn LE, Homstein J, Hilsenrath E. 2004. The ozone mapping and profiler suite (OMPS). The next generation of US ozone monitoring instruments. *Proceedings on Geoscience and Remote Sensing Symposium IGARSS*, Anchorage, AK, 20–24 September 2004. IEEE: Piscataway, NJ, DOI: DOI10.1109/IGARSS.2004.1368968.

Flynn LE, McNamara D, Beck CT, Petropavlovskikh I, Beach E, Pachepsky Y, Li YP, Deland M, Huang LK, Long CS, Tiruchirapalli R, Taylor S. 2009. Measurements and products from the Solar Backscatter Ultraviolet (SBUV/2) and Ozone Mapping and Profiler Suite (OMPS) instruments. *International Journal of Remote Sensing* **30**: 4259–4272.

Frankenberg C, Bergamaschi P, Butz A, Houweling S, Meirink JF, Notholt L, Petersen AK, Schrijver H, Warneke T, Aben I. 2008. Tropical methane emissions: a revised view from SCIAMACHY onboard ENVISAT. *Geophysical Research Letters* **35**: L15811.

Frankenberg C, Meirink JF, Bergamaschi P, Goede APH, Heimann M, Körner S, Platt U, van Weele M, Wagner T. 2006. Satellite chartography of atmospheric methane from SCIAMACHYon board ENVISAT: analysis of the years 2003 and 2004. *Journal of Geophysical Research* **111**: D07303.

Frankenberg C, Meirink JF, van Weele M, Platt U, Wagner T. 2005. Assessing methane emissions from global space-borne observations. *Science* **308**: 1010–1014.

Fraser RS, Ferrare RA, Kaufman YJ, Markham BL, Mattoo S. 1992. Algorithm for atmospheric correction of aircraft and satellite imagery. *International Journal of Remote Sensing* **13**: 541–557.

Fraser RS, Kaufman YJ, Mahoney RL. 1984. Satellite measurements of aerosol mass and transport. *Atmospheric Environment* **18**: 2577–2584.

Frederick JE, Cebula RP, Heath DF. 1986. Instrument characterization for the detection of long-term changes in stratospheric ozone: an analysis of the SBUV/2 radiometer. *Journal of Atmospheric and Oceanic Technology* **3**: 472–480.

Freilich MH, Vanhoff BA. 2006. The accuracy of preliminary WindSat vector wind measurements: comparisons with NDBC buoys and QuikSCAT. *IEEE Transactions on Geoscience and Remote Sensing* **44**: 622–637.

Frey RA, Ackerman SA, Liu Y, Strabala KI, Zhang H, Key JR, Wang X. 2008. Cloud detection with MODIS. Part I: improvements in the MODIS cloud mask for collection 5. *Journal of Atmospheric and Oceanic Technology* **25**: 1057–1072.

Frey RA, Baum BA, Menzel WP, Ackerman SA, Moeller CC, Spinhirne JD. 1999. A comparison of cloud top heights computed from airborne lidar and MAS radiance data using CO2-slicing. *Journal of Geophysical Research* **104**: 24547–24555.

Fritz S, Winston JS. 1962. Synoptic use of radiation measurements from satellite TIROS II. *Monthly Weather Review* **90**: 1–9.

Froidevaux L, Livesey NJ, Read WG, Jiang YB, Jimenez C, Filipiak MJ, Schwartz MJ, Santee ML, Pumphrey HC, Jiang JH, Wu DL, Manney GL, Drouin BJ, Waters JW, Fetzer EJ, Bernath PF, Boone CD, Walker KA, Jucks KW, Toon GC, Margitan JJ, Sen B, Webster CR, Christensen LE, Elkins JW, Atlas E, Lueb RA, Hendershot R. 2006. Early validation analyses of atmospheric profiles from EOS MLS on the aura Satellite. *IEEE Transactions on Geoscience and Remote Sensing* **44**: 1106–1121.

Früh B, Bendix J, Nauss T, Paulat M, Pfeiffer A, Schipper JW, Thies B, Wernli H. 2007. Verification of precipitation from regional climate simulations and remote-sensing observations with respect to ground-based observations in the upper Danube catchment. *Meteorologische Zeitschrift* **16**: 275–293.

Fujita T. 1968. Present status of cloud velocity computations from ATS-1 and ATS-3. *Advances in Space Research* **9**: 557–570.

Funke B, Lopez-Puertas M, Bermejo-Pantaléon D, von Clarmann T, Stiller GP, Höpfner M, Grabowski U, Kaufmann M. 2007. Analysis of nonlocal thermodynamic equilibrium CO 4.7 μm fundamental, isotopic, and hot band emissions measured by the Michelson interferometer for passive atmospheric sounding on Envisat. *Journal of Geophysical Research* **112**: D11305.

Gaiser PW, St. Germain KM, Twarog EM, Poe GA, Purdy W, Richardsom D, Grossman W, Jones WL, Spencer D, Golba G, Cleveland J, Choy L, Bevilacqua RM, Chang PS. 2004. The WindSat spaceborne polarimetric microwave radiometer: sensor description and early orbit performance. *IEEE Transactions on Geoscience and Remote Sensing* **42**: 2347–2361.

Gao BC, Kaufman YJ. 2003. Water vapor retrievals using moderate resolution imaging spectroradiometer (MODIS) near-infrared channels. *Journal of Geophysical Research* **108**(D13): 4389.

Gedzelman SD, Hindman E, Zhang X, Lawrence J, Gamache J, Black M, Black R, Dunion J, Willoughby H. 2003. Probing Hurricanes with stable isotopes of rain and water vapor. *Monthly Weather Review* **131**: 1112–1127.

Geier EB, Green RN, Kratz DP, Minnis P, Miller WF, Nolan SK, Franklin CB. 2003. *CERES Data Management System Single Satellite Footprint TOA/Surface Fluxes and Clouds (SSF) Collection Document, Release 2 Version 1*. NASA/SAIC: Hampton, VA; 13 pp.

George M, Clerbaux C, Hurtmans D, Turquety S, Coheur PF, Pommier M, Hadji-Lazaro J, Edwards DP, Worden H, Luo M, Rinsland C, McMillan W. 2009. Carbon monoxide distributions from the IASI/METOP mission: evaluation with other space-borne remote sensors. *Atmospheric Chemistry and Physics* **9**: 8317–8330.

Ghosh A, Pal N, Das J. 2006. A fuzzy rule based approach to cloud cover estimation. *Remote Sensing of Environment* **100**: 531–549.

Gille JC, Bailey PL, Craig RA, House FB, Anderson GP. 1980. Sounding the stratosphere and mesosphere by infrared limb scanning from space. *Science* **208**: 397–399.

Gille JC, Barnett JJ, Whitney JC, Dials MA, Woodard DM, Rudolf W, Lambert A, Mankin W. 2003. The High resolution dynamics limb sounder (HIRDLS) experiment on Aura. *Proceedings of the SPIE* **5152**: 162–171.

Gille JC, Barnett J, Arter P, Barker M, Bernath P, Boone C, Cavanaugh C, Chow J, Coffey M, Craft J, Craig C, Dials M, Dean V, Eden T, Edwards DP, Francis G, Halvorson C, Harvey L, Hepplewhite C, Khosravi R, Kinnison D, Krinsky C, Lambert A, Lee H, Lyjak L, Loh J, Mankin W, Massie S, McInerney J, Moorhouse J, Nardi B, Pockman D, Randall C, Reburn J, Rudolf W, Schwartz M, Serafin J, Stone K, Torpy B, Walker K, Waterfall A, Watkins R, Whitney J, Woodard D, Young G. 2008. The High resolution dynamics limb sounder (HIRDLS): experiment overview, recovery and validation of initial temperature data. *Journal of Geophysical Research* **113**: D16S43.

Gille JC, Russell JM III. 1984. The limb infrared monitor of the stratosphere: experiment description, performance, and results. *Journal of Geophysical Research* **89**: 5125–5140.

Gille JC, Russell JM, Bailey PL, Remsberg EE, Gordley LL, Evans WFJ, Fischer H, Gaudrud BW, Girard A, Harries JE, Beck SA. 1984. Accuracy and precision of the nitric acid concentration determined by the limb infrared monitor of the stratosphere experiment on the Nimbus 7. *Journal of Geophysical Research* **89**: 5179–5190.

Gómez-Chova L, Camps-Valls G, Bruzzone L, Calpe-Maravilla J. 2010. Mean map kernel methods for semisupervised cloud classification. *IEEE Transactions on Geoscience and Remote Sensing* **48**: 207–220.

Goodrum G, Kidwell KB, Winston W (eds). 1999. *NOAA KLM User's Guide*. NOAA, NOAANESDIS/NCDC: Suitland, MD.

Gopalan K, Wang NY, Ferraro R, Liu C. 2010. Status of the TRMM 2A12 land precipitation algorithm. *Journal of Atmospheric and Oceanic Technology* **27**: 1343–1354.

Grandell J, Stuhlmann R. 2007. Limitations to a geostationary infrared sounder due to diffraction: The Meteosat Third Generation Infrared Sounder (MTG IRS). *Journal of Atmospheric Oceanic Technology* **24**: 1740–1749.

Greenwald TJ, Christopher SA. 1999. Daytime variation of marine stratocumulus microphysical properties as observed from geostationary satellite. *Geophysical Research Letters* **26**: 1723–1726.

Greenwald TJ, Christopher SA. 2000. The GOES I-M imagers: new tools for studying microphysical properties of boundary layer stratiform clouds. *Bulletin of the American Meteorological Society* **81**: 2607–2619.

Greenwald TJ, Christopher SA, Chou J. 1997. Cloud liquid water path comparisons from passive microwave and solar reflectance satellite measurements: assessment of sub-field-of-view cloud effects in microwave retrievals. *Journal of Geophysical Research* **102**: 19585–19596.

Greenwald TJ, Christopher SA, Chou J, Liljegren JC. 1999. Intercomparison of cloud liquid water path derived from the GOES-9 imager and ground based microwave radiometers for continental stratocumulus. *Journal of Geophysical Research* **104**: 9251–9260.

Greenwald TJ, L'Ecuyer TS, Christopher SA. 2007. Evaluating specific error characteristics of microwave-derived cloud liquid water path products. *Geophysical Research Letters* **34**: L22807.

Greenwald TJ, Stephens GL, Vonder Haar TH, Jackson DL. 1993. A physical retrieval of cloud liquid water over the global oceans using special sensor microwave/imager (SSM/I) observations. *Journal of Geophysical Research* **98**: 18471–18488.

Grey WMF, North PRJ, Los SO, Mitchell RM. 2006. Aerosol optical depth and land surface reflectance from multiangle AATSR measurements: global validation and intersensor comparisons. *IEEE Transactions on Geoscience and Remote Sensing* **44**: 2184–2197.

Griffith CG, Woodley WL, Grube PG, Martin DW, Stout J, Sikdar DN. 1978. Rain estimation from geosynchronous satellite imagery – visible and infrared studies. *Monthly Weather Review* **106**: 1153–1171.

Griggs M. 1983. Satellite measurements of tropospheric aerosols. *Advances in Space Research* **2**: 109–118.

Grody NC. 1991. Classification of snow cover and precipitation using the special sensor microwave imager. *Journal of Geophysical Research* **96**: 7423–7435.

Grody NC, Weng F, Ferraro RR. 1998. Comparison between AMSU and DSMP measurements. *Proceeding of 9th Conference on Satellite Meteorology and Oceanography*, Paris, FR, 25–29 May 1998. American Meteorological Society: Boston, MA; 476–479.

Grody NC, Zhao J, Ferraro R, Weng F, Boers R. 2001. Determination of precipitable water and cloud liquid water over oceans from the NOAA-15 advanced microwave sounding unit. *Journal of Geophysical Research* **106**: 2943–2954.

Gruber A. 1973. Estimating rainfall in regions of active convection. *Journal of Applied Meteorology* **12**: 110–118.

Hamada A, Nishi N. 2010. Development of a cloud-top height estimation method by geostationary satellite split-window measurements trained with CloudSat data. *Journal of Applied Meteorology and Climatology* **49**: 2035–2049.

Hamada A, Nishi N, Iwasaki S, Ohno Y, Kumagai H, Okamoto H. 2008. Cloud type and top height estimation for tropical upper-tropospheric clouds using GMS-5 split-window measurements combined with cloud radar measurements. *Scientific Online Letters on the Atmosphere* **4**: 57–60.

Hamazaki T, Kaneko Y, Kuze A, Kondo K, Nakamura T, Seki Y. 2004. Greenhouse gases observing satellite. *Proceedings of the IEICE General Conference, Tokyo*, 10 March 2004.

Han Q, Brenguier JL, Kuo KS, Naeger A. 2009. A new IR technique for monitoring low cloud properties using geostationary satellite data. *Atmospheric Science Letters* **10**: 115–121.

Han Q, Rossow WB, Lacis AA. 1994. Near-global survey of effective droplet radii in liquid water clouds using ISCCP data. *Journal of Climate* **7**: 465–497.

Hanisco TF, Moyer EJ, Weinstock EM, St. Clair JM, Sayres DS, Smith JB, Lockwood R, Anderson JG. 2007. Observations of deep convective influence on stratospheric water vapor and its isotopic composition. *Geophysical Research Letters* **34**: L048141–L048145.

Harries JE, Russel JE, Hanafin JA, Brundley H, Futyan J, Rufus J, Kellock S, Matthews G, Wrigley R, Last A, Mueller J, Mossavati R, Ashmall J, Sawyer E, Parker D, Caldwell M, Allan PM, Smith A, Bates MJ, Coan B, Stewart BC, Lepine DR, Cornwall LA, Corney DR, Ricketts MJ, Drummond D, Smart D, Cutler R, Dewitte S, Clerbaux N, Gonzalez L, Ipe A, Bertrand C, Joukoff A, Crommelynck D, Nelms N, Llewellyn-Jones DT, Butcher G, Smith GL, Szewczyk ZP, Mlynczak PE, Slingo A, Allan RP, Ringer MA. 2005. The geostationary Earth radiation budget project. *Bulletin of the American Meteorological Society* **86**: 945–60.

Harrison EF, Minnis P, Barkstrom BR, Ramanathan V, Cess RD, Gibson GG. 1990. Seasonal variation of cloud radiative forcing derived from the Earth radiation budget experiment. *Journal of Geophysical Research* **95**: 18687–18703.

Hartmann DL. 2002. Climate change: tropical surprises. *Science* **295**: 811–812.

Hasekamp OP, Landgraf J. 2001. Ozone profile retrieval from backscattered ultraviolet radiances: The inverse problem solved by regularization. *Journal of Geophysical Research* **106**: 8077–8088.

Hayden CM. 1988. GOES-VAS simultaneous temperature-moisture retrieval algorithm. *Journal of Applied Meteorology* **27**: 705–733.

Hayden CM, Menzel WP, Nieman SJ, Schmit TJ, Velden CS. 1993. Recent progress in methods for deriving winds from satellite data at NESDIS/CIMSS. *Advances in Space Research* **14**: 99–110.

Haynes JM, L'Ecuyer TS, Stephens GL, Miller SD, Mitrescu C, Wood NB, Tanelli S. 2009. Rainfall retrieval over the ocean with spaceborne W-band radar. *Journal of Geophysical Research* **114**: D00A22.

Heath DF, Krueger AJ, Roeder HA, Henderson BD. 1975. The solar backscatter ultraviolet and total ozone mapping spectrometer (SBUV/TOMS) for Nimbus G. *Optical Engineering* **14**: 323–331.

Higurashi A, Nakajima T. 1999. Development of a two-channel aerosol retrieval algorithm on a global scale using NOAA AVHRR. *Journal of the Atmospheric Sciences* **56**: 924–941.

Hilsenrath E, Cebular RP, Deland MT, Laamann K, Taylor S, Wellemeyer C, Bhartia PK. 1995. Calibration of the Noaa-11 Solar Backscatter Ultraviolet (SBUV/2) ozone data set from 1989 to 1993 using in-flight calibration data and SSBUV. *Journal of Geophysical Research* **100**: 1351–1366.

Hoffman RN. 1993. A preliminary study of the impact of the ERS 1 C-band scatterometer wind data on the ECMWF global data assimilation system. *Journal of Geophysical Research* **98**: 10233–10244.

Hoffman RN, Leidner SM. 2005. An introduction to the near-real-time QuikSCAT data. *Weather and Forecasting* **20**: 476–493.

Hollinger J. 1989. *DMSP Special Sensor Microwave/Imager Calibration/Validation*, Final Report, Vol. 1. Naval Research Laboratory: Washington, DC; 153.

Holmlund K. 1995. Half hourly wind data from satellite derived water vapour measurements. *Advances in Space Research* **16**: 59–68.

Hong Y, Hsu KL, Sorooshian S, Gao X. 2004. Precipitation estimation from remotely sensed imagery using an artificial neural network cloud classification system. *Journal of Applied Meteorology* **43**: 1834–1853.

Hoogen R, Rozanov VV, Burrows JP. 1999. Ozone profiles from GOME satellite data: Algorithm description and first validation. *Journal of Geophysical Research* **104**: 8263–8280.

Horvath A, Davies R. 2001a. Feasibility and error analysis of cloud motion wind extraction from near-simultaneous multiangle MISR measurements. *Journal of Atmospheric and Oceanic Technology* **18**: 591–608.

Horvath A, Davies R. 2001b. Simultaneous retrieval of cloud motion and height from polar-orbiter multiangle measurements. *Geophysical Research Letters* **28**: 2915–2918.

Horvath A, Gentemann C. 2007. Cloud-fraction-dependent bias in satellite liquid water path retrievals of shallow, non-precipitating clouds. *Geophysical Research Letters* **34**: L22806.

Houshangpour A, John VO, Buehler SA. 2005. Retrieval of upper tropospheric water vapor and upper tropospheric humidity from AMSU radiances. *Atmospheric Chemistry and Physics* **5**: 2019–2028.

Hsu K, Bellerby T, Sorooshian S. 2009. LMODEL: a satellite precipitation methodology using cloud development modeling. Part II: validation. *Journal of Hydrometeorology* **10**: 1096–1108.

Hsu KL, Gao X, Sorooshian S. 2002. Rainfall estimation using cloud texture classification mapping. *Proceedings of 1st IPWG Workshop*, Madrid, Spain, 23–27 September 2002. IMGW: Krakow; 140–144.

Hsu NC, Tsay SC, King MD, Herman JR. 2004. Aerosol properties over brightreflecting source regions. *IEEE Transactions on Geoscience and Remote Sensing* **42**: 557–569.

Hu Y, Winker D, Vaughan M, Lin B, Omar A, Trepte C, Flittner D, Yang P, Nasiri SL, Baum B, Holz R, Sun W, Liu Z, Wang Z, Young S, Stamnes K, Huang J, Kuehn R. 2009. CALIPSO/CALIOP Cloud Phase Discrimination Algorithm. *J. Atmos. Oceanic Technol.* **26**: 2293–2309.

Huang X, Yang W, Loeb NG, Ramaswamy V. 2008. Spectrally resolved fluxes derived from collocated AIRS and CERES measurements and their application in model evaluation: clear sky over the tropical oceans. *Journal of Geophysical Research* **113**: D09110.

Hubert LF, Whitney LF Jr. 1971. Wind estimation from geostationary-satellite pictures. *Monthly Weather Review* **99**: 665–672.

Huffman GJ, Adler RF, Bolvin DT, Gu G, Nelkin EJ, Bowman KP, Hong Y, Stocker EF, Wolff DB. 2007. The TRMM multisatellite precipitation analysis (TMPA): Quasi-global, multiyear, combined-sensor precipitation estimates at fine scales. *Journal of Hydrometeorology* **8**: 38–55.

Husar RB, Prospero J, Stowe LL. 1997. Characterization of tropospheric aerosols over the oceans with the NOAA AVHRR optical thickness operational product. *Journal of Geophysical Research* **102**: 16889–16909.

Hutchison KD, Roskovensky J, Jackson J, Heidinger A, Pavolonis MJ, Frey R, Kopp T. 2005. Automated cloud detection and typing of data collected by the Visible Infrared Imager Radiometer Suite (VIIRS). *International Journal of Remote Sensing* **20**: 4681–4706.

Iguchi T, Kozu T, Meneghini R, Awaka J, Okamoto K. 2000. Rain-profiling algorithm for the TRMM precipitation radar. *Journal of Applied Meteorology* **39**: 2038–2052.

Iguchi T, Meneghini R. 1994. Intercomparison of single-frequency methods for retrieving a vertical rain profile from airborne or spaceborne radar data. *Journal of Atmospheric and Oceanic Technology* **11**: 1507–1516.

IPCC. 2007. In *Climate CHANGE 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds). Cambridge University Press: Cambridge and New York, NY; 996 pp.

Irie H, Sugita T, Nakajima H, Yokota T, Oelhaf H, Wetzel G, Toon GC, Sen B, Santee ML, Terao Y, Saitoh N, Ejiri MK, Tanaka T, Kondo Y, Kanzawa H, Kobayashi H, Sasano Y. 2006. Validation of stratospheric nitric acid profiles observed by improved limb atmospheric spectrometer (ILASII). *Journal of Geophysical Research* **111**: D11S03.

Isaacs RG, Hoffman RN, Kaplan LD. 1986. Satellite remote sensing of meteorological parameters for global numerical weather prediction. *Reviews of Geophysics* **24**: 701–743.

Isaksen L, Janssen P. 2004. Impact of ERS scatterometer winds in ECMWF's assimilation system. *Quarterly Journal of the Royal Meteorological Society* **130**: 1793–1814.

Jackson DL, Bates JJ. 2001. Upper tropospheric humidity algorithm assessment. *Journal of Geophysical Research* **106**: 32259–32270.

Jaegle L, Martin RV, Chance K, Steinberger L, Kurosu TP, Jacob DJ, Modi AI, Yoboué V, Sigha-Nkamdjou L, Galy-Lacaux C. 2004. Satellite mapping of rain-induced nitric oxide emissions from soils. *Journal of Geophysical Research* **109**: D21310.

Jin X, Wu T, Li L, Shi C. 2009. Cloudiness characteristics over Southeast Asia from satellite FY-2C and their comparison to three other cloud data sets. *Journal of Geophysical Research* **114**: D17207.

Jones WL, Cardone VJ, Pierson WJ, Zec J, Rice LP, Cox A, Sylvester WB. 1999. NSCAT high resolution surface winds measurements in typhoon violet. *J. Geophys. Res.* **104**: 11247–11259.

Josset D, Pelon J, Protat A, Flamant C. 2008. New approach to determine aerosol optical depth from combined CALIPSO and CloudSat ocean surface echoes. *Geophysical Research Letters* **35**: L10805.

Joyce RJ, Janowiak JE, Arking PA, Xie P. 2004. CMORPH: a method that produces global precipitation estimates from passive microwave and infrared data at high spatial and temporal resolution. *Journal of Hydrometeorology* **5**: 487–503.

Jung T, Ruprecht E, Wagner F. 1998. Determination of cloud liquid water path over the oceans from special sensor microwave/imager (SSM/I) data using neural networks. *Journal of Applied Meteorology* **37**: 832–844.

Kachi M, Imaoka K, Fujii H, Shibata A, Kasahara M, Iida Y, Ito N, Nakagawa K, Shimoda H. 2008. Status of GCOM-W1/AMSR2 development and science activities. *Proceedings of the SPIE* **7106**: 71060.

Kahn BH, Eldering A, Braverman AJ, Fetzer EJ, Jiang JH, Fishbein E, Wu DL. 2007. Toward the characterization of upper tropospheric clouds using atmospheric infrared sounder and microwave limb sounder observations. *Journal of Geophysical Research* **112**: D05202.

Kaila VK, Kumar K, Sundarmurthy AS, Ramkrishnan TK, Prasad S, Desai MVS, Jayaraman PS, Manikiam B. 2002. METSAT -a unique mission for weather and climate. *Current Science* **83**: 1081–1088.

Karlsson KG. 1989. Development of an operational cloud classification model. *International Journal of Remote Sensing* **10**: 687–693.

Karlsson KG. 1996. *Cloud Classification with the SCANDIA Model, Swedish Meteorological and Hydrological Institute Reports on Meteorology and Climatology, Vol. 67*. SMHI: Norrköping; 36.

Kärner O. 1997. Normal mixture approach for cloud detection. In *IRS'96 Current Problems in Atmospheric Radiation*, Smith WL, Stammes K (eds). A. Deepak Publishing: Hampton, VA; 599–602.

Karouche N, Raju G. 2010. Megha-Tropiques satellite mission: sensors performances. *Proceedings of the SPIE* **7826**: 78260Q.

Kato S, Marshak A. 2009. Solar zenith and viewing geometry dependent errors in satellite retrieved cloud optical thickness: Marine stratocumulus case. *Journal of Geophysical Research* **114**: D01202.

Kato S, Rose FG, Charlock TP. 2005. Computation of domain-averaged irradiance using satellite-derived cloud properties. *Journal of Atmospheric and Oceanic Technology* **22**: 146–164.

Kaufman YJ, Gobron N, Pinty B, Widlowski JL, Verstraete MM. 2002. Relationship between surface reflectance in the visible and mid-IR used in MODIS aerosol algorithm – theory. *Geophys. Res. Lett.* **29**: 2116.

Kaufman YJ, Nakajima T. 1993. Effect of Amazon smoke on cloud microphysics and albedo-analysis from satellite imagery. *Journal of Applied Meteorology* **32**: 729–744.

Kaufman YJ, Sendra C. 1988. Algorithm for automatic atmospheric corrections to visible and near-IR satellite imagery. *International Journal of Remote Sensing* **9**: 1357–1381.

Kaufman YJ, Tanre D, Léon JF, Pelon J. 2003. Retrievals of profiles of fine and coarse aerosols using lidar and radiometric space measurements. *IEEE Transactions on Geoscience and Remote Sensing* **41**: 1743–1754.

Kaufman YJ, Tanre D, Remer LA, Vermote EF, Chu A, Holben BN. 1997. Operational remote sensing of tropospheric aerosol over land from EOS moderate resolution imaging spectroradiometer. *Journal of Geophysical Research* **102**: 17051–17067.

Kaur R, Ganju A. 2008. Cloud classification in NOAA AVHRR imageries using spectral and textural features. *Journal of the Indian Society of Remote Sensing* **36**: 167–174.

Keppler F, Hamilton JTG, Braß M, Röckmann T. 2006. Methane emissions from terrestrial plants under aerobic conditions. *Nature* **439**: 187–191.

Kerrache M, Schmetz J. 1988. A precipitation index from the ESOC climatological data set. *ESA Journal* **12**: 379–383.

Key J, Santek D, Velden CS, Bormann N, Thepaut JN, Riishojgaard LP, Zhu Y, Menzel WP. 2002. Cloud-drift and water vapor winds in the polar regions from MODIS. *IEEE Transactions on Geoscience and Remote Sensing* **41**: 482–492.

Khosravi R, Lambert A, Lee H, Gille J, Barnett J, Francis G, Edwards D, Halvorson C, Massie S, Craig C, Krinsky C, McInerney J, Stone K, Eden T, Nardi B, Hepplewhite C, Mankin W, Coffey M. 2009. Overview and characterization of retrievals of temperature, pressure, and atmospheric constituents from the high resolution dynamics limb sounder (HIRDLS) measurements. *Journal of Geophysical Research* **114**: D20304.

Kidd C. 2001. Satellite rainfall climatology: a review. *International Journal of Climatology* **21**: 1041–1066.

Kidd CK, Kniveton DR, Todd MC, Bellerby TJ. 2003. Satellite rainfall estimation using combined passive microwave and infrared algorithms. *Journal of Hydrometeorology* **4**: 1088–1104.

Kidd C, Levizzani V. 2011. Status of satellite precipitation retrievals. *Hydrol. Earth Sys. Sci.* **15**: 1109–1116.

Kidd C, Levizzani V, Bauer P. 2009. A review of satellite meteorology and climatology at the start of the twenty-first century. *Progress in Physical Geography* **33**: 474–489.

Kidder SQ, Goldberg MD, Zehr RM, DeMaria M, Purdom JFW, Velden CS, Grody NC, Kusselson SJ. 2000. Satellite analysis of tropical cyclones using the advanced microwave sounding unit (AMSU). *Bulletin of the American Meteorological Society* **81**: 1241–1259.

Kidder SQ, Gray WM, Vonder Haar TH. 1978. Estimating tropical cyclone central pressure and outer winds from satellite microwave data. *Monthly Weather Review* **106**: 1458–1464.

Kidder SQ, Gray WM, Vonder Haar TH. 1980. Tropical cyclone outer surface winds derived from satellite microwave sounder data. *Monthly Weather Review* **108**: 144–152.

Kidder SQ, Vonder Haar TH. 1995. *Satellite Meteorology: An Introduction*. Academic Press: Salt Lake City, UT; 466 pp.

Kiehl JT, Briegleb BP. 1993. The relative role of sulfate aerosols and greenhouse gases in climate forcing. *Science* **260**: 311–314.

Kim D, Lyzenga DR. 2008. Efficient model-based estimation of atmospheric transmittance and ocean wind vectors from WindSat data. *IEEE Transactions on Geoscience and Remote Sensing* **46**: 2288–2297.

Kim MJ, Weinman JA, Olson WS, Chang DE, Skofronick-Jackson G, Wang JR. 2008. A physical model to estimate snowfall over land using AMSU-B observations. *Journal of Geophysical Research* **113**: D09201.

King MD, Kaufman YJ, Menzel WP, Tanré D. 1992. Remote sensing of cloud, aerosol, and water vapor properties from the moderate resolution imaging spectrometer (MODIS). *IEEE Transactions on Geoscience and Remote Sensing* **30**: 2–27.

King MD, Kaufman YJ, Tanré D, Nakajima T. 1999. Remote sensing of tropospheric aerosols from space: past, present and future. *Bulletin of the American Meteorological Society* **80**: 2229–2259.

King MD, Menzel WP, Kaufman YJ, Tanre D, Gao BC, Platnick S, Ackerman SA, Remer LA, Pincus R, Hubanks PA. 2003. Cloud and aerosol properties, precipitable water, and profiles of temperature and water vapor from MODIS. *IEEE Transactions on Geoscience and Remote Sensing* **41**: 442–458.

King MD, Tsay SC, Platnick SE, Wang M, Liou KN. 1997. *Cloud Retrieval Algorithms for MODIS: Optical Thickness, Effective Particle Radius, and Thermodynamic Phase*, MODIS Algorithm Theoretical Basis Document No. ATBD-MOD-05. NASA: Greenbelt, MD; 83 pp.

Kishtawal CM, Deb SK, Pal PK, Joshi PC. 2009. Estimation of atmospheric motion vectors from Kalpana-1 imagers. *Journal of Applied Meteorology and Climatology* **48**: 2410–2421.

Klaes KD, Cohen M, Buhler Y, Schlüssel P, Munro R, Luntama JP, von Engeln A, Clérigh EÓ, Bonekamp H, Ackermann J, Schmetz J. 2007. An introduction to the EUMETSAT polar system. *Bulletin of the American Meteorological Society* **88**: 1085–1096.

Kleespies TJ. 2007. Relative information content of the advanced technology microwave sounder and the combination of the advanced microwave sounding unit and the microwave humidity sounder. *IEEE Transactions on Geoscience and Remote Sensing* **45**: 2224–2227.

Klenk KF, Bhartia PK, Kaveeshwar VB, McPeters RD, Smith PM, Fleig AJ. 1982. Total ozone determination from the backscattered ultraviolet (BUV) experiment. *Journal of Applied Meteorology* **21**: 1672–1684.

Kley D, Russel JM. 2001. SPARC assessment of upper tropospheric and stratospheric water vapour. *SPARC Newsletter* **16**: 11–16.

Knapp KR, Frouin R, Kondragunta S, Prados A. 2005. Toward aerosol optical depth retrievals over land from GOES visible radiances: determining surface reflectance. *International Journal of Remote Sensing* **26**: 4097–94116.

Kokhanovsky AA, Jourdan O, Burrows JP. 2006. The cloud phase discrimination from a satellite. *IEEE Geoscience and Remote Sensing Letters* **3**: 103–106.

Kokhanovsky AA, Rozanov VV, Burrows JP, Eichmann KU, Lotz W, Vountas M. 2005. The SCIAMACHY cloud products: algorithms and examples from ENVISAT. *Advances in Space Research* **36**: 789–799.

Kokhanovsky AA, Rozanov VV, Zege PE, Bovensmann H, Burrows JP. 2003. A semianalytical cloud retrieval algorithm using backscattered radiation in 0.4–2.4 mm spectral region. *J. Geophys. Res.* **108**: 4008.

Kongoli C, Pellegrino P, Ferraro RR, Grody NC, Meng H. 2003. A new snowfall detection algorithm over land using measurements from the advanced microwave sounding unit (AMSU). *Geophysical Research Letters* **30**: 1756.

Koshak WJ, Stewart MF, Christian HJ, Bergstrom JW, Hall JM, Solakiewicz RJ. 2000. Laboratory calibration of the optical transient detector and the lightning imaging sensor. *Journal of Atmospheric and Oceanic Technology* **17**: 905–915.

Krasnopolsky VM, Breaker LC, Gemmill WH. 1995. A neural network as a nonlinear transfer function model for retrieving surface wind speeds from the special sensor microwave imager. *Journal of Geophysical Research* **100**: 11033–11045.

Kriebel KT, Gesell G, Kästner M, Mannstein H. 2003. The cloud analysis tool APOLLO: improvements and validations. *International Journal of Remote Sensing* **24**: 2389–2408.

Krimchansky A, Machi D, Cauffman S, Davis M. 2004. Next generation geostationary operational environmental satellite (GOES-R series): a space segment overview. *Proceedings of SPIE* **5570**: 155–164.

Krotkov NA, Barthia PK, Herman JR, Fioletov V, Kerr J. 1998. Satellite estimation of spectral surface UV irradiance in the presence of tropospheric aerosols. *Journal of Geophysical Research* **103**: 8779–8793.

Krotkov NA, Herman JR, Barthia PK, Fioletov V, Ahmad Z. 2001. Satellite estimation of spectral surface UV irradiance 2. Effects of homogeneous clouds and snow. *Journal of Geophysical Research* **106**: 11743–11759.

Krotkov NA, McClure B, Dickerson RR, Carn SA, Can L, Bhartia PK, Yang K, Krueger AJ, Li Z, Levelt PF, Chen H, Wang P, Daren L. 2008. Validation of SO2 retrievals from the Ozone Monitoring Instrument (OMI) over NE China. *Journal of Geophysical Research* **113**: D16S40.

Krueger AJ. 1983. Sighting of EL Chichon sulfur dioxide clouds with the Nimbus 7 total ozone mapping spectrometer. *Science* **220**: 1277–1379.

Krueger AJ, Schaefer SJ, Krotkov N, Bluth G, Barker S. 2000. Ultraviolet remote sensing of volcanic emissions. In *Remote Sensing of Active Volcanism*, *Geophysical Monograph Series, Vol. 116*, Mouginis-Mark PJ, Crisp JA, Fink JH (eds). AGU: Washington, DC; 25–43.

Krueger AJ, Walter LS, Bhartia PK, Schnetzler CC, Krotkov NA, Sprod I, Bluth GJS. 1995. Volcanic sulfur dioxide measurements from the total ozone mapping spectrometer instruments. *Journal of Geophysical Research* **100**: 14057–14076.

Kühnlein M, Thies B, Nauss T, Bendix J. 2010. Rainfall-rate assignment using MSG SEVIRI data – a promising approach to spaceborne rainfall-rate retrieval for midlatitudes. *Journal of Applied Meteorology Climatology* **49**: 1477–1495.

Kulawik SS, Bowman KW, Luo M, Rodgers CD, Jourdain L. 2008. Impact of nonlinearity on changing the a priori of trace gas profile estimates from the Tropospheric Emission Spectrometer (TES). *Atmospheric Chemistry and Physics* **8**: 3081–3092.

Kuligowski RJ. 2002. A self-calibrating real-time GOES rainfall algorithm for short-term rainfall estimates. *Journal of Hydrometeorology* **3**: 112–130.

Kummerow C, Barnes W, Kozu T. 1998. The tropical rainfall measuring mission (TRMM) sensor package. *Journal of Atmospheric and Oceanic Technology* **15**: 809–817.

Kummerow C, Giglio L. 1994. A passive microwave technique for estimating rainfall and vertical structure information from space. 1. Algorithm description. *Journal of Applied Meteorology* **33**: 3–18.

Kummerow C, Giglio L. 1995. A method for combining passive microwave and infrared rainfall observations. *Journal of Atmospheric and Oceanic Technology* **12**: 33–45.

Kummerow C, Hong Y, Olson WS, Yang S, Adler RF, McCollum J, Ferraro R, Petty G, Shin DB, Wilheit TT. 2001. The evolution of the goddard profiling algorithm (GPROF) for rainfall estimation from passive microwave sensors. *Journal of Applied Meteorology* **40**: 1801–1820.

Kunkee DB, Poe GA, Boucher DJ, Swadley SD, Hong Y, Wessel JE, Uliana EA. 2003. Design and evaluation of the first special sensor microwave imager/sounder. *IEEE Transactions on Geoscience and Remote Sensing* **46**: 863–883.

Kurino T. 1997. A satellite infrared technique for estimating 'deep/shallow' precipitation. *Advances in Space Research* **19**: 511–514.

Kyrölä E, Tamminen J, Leppelmeier GW, Sofieva V, Hassinen S, Bertaux JL, Hauchecorne A, Dalaudier F, Cot C, Korablev O, d'Andon OF, Barrot G, Mangin A, Theodore B, Guirlet M, Etanchaud F, Snoeij P, Koopman R, Saavedra L, Fraisse R, Fussen D, Vanhellemont F. 2004. GOMOS on Envisat: an overview. *Advances in Space Research* **33**: 1020–1028.

Kyrölä E, Tamminen J, Sofieva V, Bertaux JL, Hauchecorne A, Dalaudier F, Fussen D, Vanhellemont F, Fanton d'Andon O, Barrot G, Guirlet M, Fehr T, Saavedra de Miguel L. 2010. GOMOS O3, NO2, and NO3 observations in 2002–2008. *Atmospheric Chemistry and Physics* **10**: 7723–7738.

Lang R, Williams JE, van der Zande WJ, Maurellis AN. 2003. Application of the spectral structure parameterization technique: retrieval of total water vapor columns from GOME. *Atmospheric Chemistry and Physics* **3**: 145–160.

Laurent H. 1993. Wind extraction from Meteosat water vapor channel image data. *Journal of Applied Meteorology* **32**: 1124–1133.

Layberry R, Kniveton DR, Todd MC, Kidd C, Bellerby TC. 2006. Daily precipitation over Southern Africa: a new resource for climate studies. *Journal of Hydrometeorology* **7**: 149–159.

Lee TF, Miller SD, Turk FJ, Schueler C, Julian R, Deyo S, Dills P, Wang S. 2006. The NPOESS/VIIRS day/night visible sensor. *Bulletin of the American Meteorological Society* **87**: 191–199.

Lee C, Richter A, Burrows JP, Lee H, Kim YJ, Lee YG, Choi BC. 2008. Impact of transport of sulfur dioxide from the Asian continent on the air quality over Korea during May 2005. *Atmospheric Environment* **42**: 1461–1475.

Lee TE, Turk FJ, Richardson K. 1997. Stratus and fog products using GOES-8-9 3.9-lm data. *Weather and Forecasting* **12**: 664–677.

Lee Y, Wahba G, Ackerman SA. 2004. Cloud classification of satellite radiance data by multicategory support vector machines. *Journal of Atmospheric and Oceanic Technology* **21**: 159–169.

Le Marshall JF, Pescod N, Seecamp R, Puri K, Spinoso C, Bowen R. 1999. Local estimation of GMS-5 water vapour motion vectors and their application to Australian region numerical weather prediction. *Australian Meteorological Magazine* **48**: 73–77.

Le Marshall JF, Smith WL, Callan GM. 1985. Hurricane Debby – An illustration of the complementary nature of VAS soundings and cloud and water vapor motion winds. *Bulletin of the American Meteorological Society* **66**: 258–263.

Lensky IM, Rosenfeld D. 1997. Estimation of precipitation area and rain intensity based on the microphysical properties retrieved from NOAA AVHRR data. *Journal of Applied Meteorology* **36**: 234–242.

Lensky IM, Rosenfeld D. 2003a. A night-rain delineation algorithm for infrared satellite data based on microphysical considerations. *Journal of Applied Meteorology* **42**: 1218–1226.

Lensky IM, Rosenfeld D. 2003b. Satellite-based insights into precipitation formation processes in continental and maritime convective clouds at nighttime. *Journal of Applied Meteorology* **42**: 1227–1233.

Leon JF, Tanre D, Pelon J, Kaufman Y, Haywood J, Chatenet B. 2003. Profiling of a Saharan dust outbreak based on a synergy between active and passive remote sensing. *Journal of Geophysical Research* **108**: 8575.

Le Roy Y, Deschaux-Beaume M, Mavrocordatos C, Borde F. 2010. SRAL, a radar altimeter designed to measure several surface types. *Proceedings of the SPIE* **7825**: 782507–782507-6.

Leue C, Wenig M, Wagner T, Klimm O, Platt U, Jähne B. 2001. Quantitative analysis of NO2 emissions from GOME satellite image sequences. *Journal of Geophysical Research* **106**: 5493–5505.

Levelt PF, van den Oord GHJ, Dobber MR, Malkki A, Visser H, de Vries J, Stammes P, Lundell JOV, Saari H. 2006. The ozone monitoring instrument. *IEEE Transactions on Geoscience and Remote Sensing* **44**: 1093–1101.

Levizzani V. 2003. Satellite rainfall estimations: new perspectives for meteorology and climate from the EURAINSAT project. *Annales Geophysicae* **46**: 363–372.

Levizzani V, Amorati R, Meneguzzo F. 2002. *A Review of Satellite Based Rainfall Estimation Methods*, European Commission Project MUSIC Report. ISAO: Bologna; 66 pp.

Levizzani V, Bauer P, Turk JF. 2007. *Measuring Precipitation From Space – EURAINSAT and the Future. Advances in Global Change Research*, Vol. 28. Springer: Dordrecht; 722 pp.

Levizzani V, Porcu F, Prodi F. 1990. Operational rainfall estimation using METEOSAT infrared imagery: an application in Italy's Arno river basin – Its potential and drawbacks. *ESA Journal* **14**: 313–323.

Levizzani V, Schmetz J, Lutz HJ, Kerkmann J, Alberoni PP, Cervino M. 2001. Precipitation estimations from geostationary orbit and prospects for Meteosat second generation. *Meteorological Applications* **8**: 23–41.

Levy RC, Remer LA, Martins JV, Kaufman YJ, Plana-Fattori A, Redemann J, Russell PB, Wenny B. 2005. Evaluation of the MODIS aerosol retrievals over ocean and land during CLAMS. *Journal of the Atmospheric Sciences* **62**: 976–992.

Levy RC, Remer LA, Mattoo S, Vermote EF, Kaufman YF. 2007. Second-generation operational algorithm: retrieval of aerosol properties over land from inversion of moderate resolution imaging spectroradiometer spectral reflectance. *Journal of Geophysical Research* **112**: D13211.

Lewis HG, Cote S, Tatnall ARL. 1997. Determination of spatial and temporal characteristics as an aid to neural network cloud classification. *International Journal of Remote Sensing* **18**: 899–915.

Li Z, Li J, Menzel WP, Schmit TJ. 2005. Imager capability on cloud classification using MODIS. *Extended Abstracts, 21st International Conference on Interactive Information Processing for Meteorology, Oceanography, and Hydrology*, San Diego, CA, 9–13 January 2005. American Meteorological Society: Boston, MA; 1–11.

Li J, Menzel WP, Yang Z, Frey RA, Ackerman SA. 2003. High-spatial-resolution surface and cloud-type classification from MODIS multispectral band measurements. *Journal of Applied Meteorology* **42**: 204–226.

Li Z, Niu F, Lee KH, Xin J, Hao WM, Nordgren B, Wang Y, Wang P. 2007. Validation and understanding of moderate resolution imaging spectroradiometer aerosol products (C5) using ground-based measurements from the handheld Sun photometer network in China. *Journal of Geophysical Research* **112**: D22S07.

Li J, Schmidt CC, Nelson JP III, Schmit TJ, Menzel WP. 2001. Estimation of total atmospheric ozone from GOES sounder radiances with high temporal resolution. *Journal of Atmospheric and Oceanic Technology* **18**: 157–168.

Li Z, Zhao X, Kahn R, Mishchenko M, Remer L, Lee KH, Wang M, Laszlo I, Nakajima T, Maring H. 2009. Uncertainties in satellite remote sensing of aerosols and impact on monitoring its long-term trend: a review and perspective. *Annales Geophysicae* **27**: 2755–2770.

Lin B, Rossow WB. 1994. Observations of cloud liquid water path over oceans: optical and microwave remote sensing methods. *Journal of Geophysical Research* **99**: 20907–20928.

Liou KN, Ou SC, Takano Y, Valero FPJ, Ackerman TP. 1990. Remote sounding of the tropical cirrus cloud temperature and optical depth using 6.5 and 10.5 μm radiometers during STEP. *Journal of Applied Meteorology* **29**: 716–726.

Liou KN, Takano Y. 2002. Interpretation of cirrus cloud polarization measurements from radiative transfer theory. *Geophysical Research Letters* **29**: 1313.

Liu G. 2004. Approximation of single scattering properties of ice and snow particles for high microwave frequencies. *Journal of the Atmospheric Sciences* **61**: 2441–2456.

Liu X, Chance K, Sioris CE, Spurr RJD, Kurosu TP, Martin RV, Newchurch MJ. 2005. Ozone profile and tropospheric ozone retrievals from global ozone monitoring experiment: algorithm description and validation. *Journal of Geophysical Research* **110**: D20307.

Liu G, Curry JA. 1993. Determination of characteristic features of cloud liquid water from satellite microwave measurements. *Journal of Geophysical Research* **98**: 5069–5092.

Liu GR, Liu CC, Kuo TH. 2001. A contrast and comparison of near-sea surface air temperature/humidity from GMS and SSM/I data with an improved algorithm. *IEEE Transactions on Geoscience and Remote Sensing* **39**: 2148–2157.

Liu Q, Weng F. 2005. One-dimensional variational retrieval algorithm of temperature, water vapor, and cloud water profiles from advanced microwave sounding unit (AMSU). *IEEE Transactions on Geoscience and Remote Sensing* **43**: 1087–1095.

Liu Y, Xia J, Shi CX, Hong Y. 2009. An improved cloud classification algorithm for China's FY-2C multi-channel images using artificial neural network. *Sensors* **9**: 5558–5579.

Livesey NJ, Filipiak MJ, Froidevaux L, Read WG, Lambert A, Santee ML, Jiang JH, Pumphrey HC, Waters JW, Cofield RE, Cuddy DT, Daffer WH, Dronin BJ, Fuller RA, Jarnot RF, Jiang YB, Knosp BW, Li QB, Perun VS, Schwartz MJ, van Snyder W, Stek PC, Thurstans RP, Wagner PA, Avery M, Browll EV, Cammas JP, Christensen LE, Diskin GS, Gao RS, Jost HJ, Loewenstein M, Lopez JD, Nedelec P, Osterman GB, Sachse GW, Webster CR. 2008. Validation of Aura microwave limb sounder O3 and CO observations in the upper troposphere and lower stratosphere. *Journal of Geophysical Research* **113**: D15S02.

Livesey NJ, van Snyder W, Read WG, Wagner PA. 2006. Retrieval algorithms for the EOS microwave limb sounder (MLS). *IEEE Transactions on Geoscience and Remote Sensing* **44**: 1144–1155.

Loeb NG, Kato S, Loukachine K, Manalo-Smith N. 2005. Angular distribution models for top-of-atmosphere radiative flux estimation from the clouds and the earth's radiant energy system (CERES) instrument on the Terra satellite. Part I: methodology. *Journal of Atmospheric and Oceanic Technology* **22**: 338–351.

Loeb NG, Priestley KJ, Kratz DP, Geier EB, Green RN, Wielicki VA, Hinton RO, Nolan SK. 2001. Determination of unfiltered radiances from the clouds and the earth's radiant energy system instrument. *Journal of Applied Meteorology* **40**: 822–835.

Loeb NG, Wielicki BA, Su W, Loukachine K, Sun W, Wong T, Priestley KJ, Matthews G, Miller WF, Davies R. 2007. Multiinstrument comparison of top-of-atmosphere reflected solar radiation. *J. Climate* **20**: 575–91.

Loiselet M, Stricker N, Menard Y, Luntama JP. 2000. GRAS-Metop's GPS-Based atmospheric sounder. *ESA Bulletin* **102**: 38–44.

Lovejoy S, Austin GL. 1979. The delineation of rain areas from visible and IR satellite data forGATE and mid-latitudes. *Atmosphere-Ocean* **17**: 77–92.

Loyola D, Balzer W, Aberle B, Bittner M, Kretschel K, Mikusch E, Muehle H, Ruppert T, Schmid C, Slijkhuis S, Spurr R, Thomas W, Wieland T, Wolfmueller M. 1997. Ground segment for ERS-2/GOME sensor at the German D-PAF. *3rd ERS Scientific Symposium*, Florence, Italy, 17–21 Mar 1997. ERS: Lausanne, CH; 591–596.

Luntama JP. 2001. EPS GRAS mission for operational GPS meteorology. *Proceedings of 14th International Technical Meeting of the Satellite Navigation of the Institute of Navigation*, Salt Lake City, UT, 11–14 Sep 2001. The Institute of Navigation: Manassas, VA.

Ma XL, Schmit TJ, Smith WL. 1999. A nonlinear physical retrieval algorithm – its application to the GOES-8/9 sounder. *Journal of Applied Meteorology* **38**: 501–513.

McClain EP, Pichel WG, Walton CC. 1985. Comparative performance of AVHRR based multichannel sea surface temperature. *Journal of Geophysical Research* **90**: 11587–11601.

McClain EP, Pichel WG, Walton CC, Ahmad Z, Sutton J. 1983. Multichannel improvements to satellite derived global sea surface temperatures. *Advances in Space Research* **2**: 43–47.

McCollum JR, Ferraro RR. 2003. Next generation of NOAA/NESDIS TMI, SSM/I, and AMSR-E microwave land rainfall algorithms. *Journal of Geophysical Research* **108**: 8382.

McIntire T, Simpson J. 2002. Arctic sea ice, cloud, water, and lead classification using neural networks and 1.6 μm data. *IEEE Transactions on Geoscience and Remote Sensing* **40**: 1956–1972.

McMillan WW, Barnet C, Strow L, Chahine MT, McCourt ML, Warner JX, Novelli PC, Korontzi S, Maddy ES, Datta S. 2005. Daily global maps of carbon monoxide from NASA's atmospheric infrared sounder. *Geophysical Research Letters* **32**: L11801.

McMillin L, Crosby D. 1984. Theory and validation of the multiple window sea surface temperature technique. *Journal of Geophysical Research* **89**: 3655–3661.

Mace GG, Marchand R, Zhang Q, Stephens G. 2007. Global hydrometeor occurrence as observed by Cloudsat: Initial observations from summer 2006. *Geophysical Research Letters* **34**: L09808.

Mace GG, Zhang Q, Vaughan M, Marchand R, Stephens G, Trepte C, Winker D. 2009. A description of hydrometeor layer occurrence statistics derived from the first year of merged Cloudsat and CALIPSO data. *Journal of Geophysical Research* **114**: D00A26.

Maddy ES, Barnet CD, Goldberg M, Sweeney C, Liu X. 2008. CO2 retrievals from the atmospheric infrared sounder: methodology and validation. *Journal of Geophysical Research* **113**: D11301, DOI: 10.1029/2007JD009402.

Madeira C. 2002. Generalized split-window algorithm for retrieving land surface temperature from MSG/SEVIRI data. *Proceedings of Land Surface Analysis SAF Training Workshop*, 8–10 Jul 2002, Lisbon.

Mao KB, Qin ZH, Shi JC, Gong P. 2004. A practical split-window algorithm for retrieving land surface temperature from MODIS data. *International Journal of Remote Sensing* **26**: 3181–3204.

Marchand RT, Mace GG, Ackerman TP. 2008. Hydrometeor detection using CloudSat: an earth orbiting 94 GHz cloud radar. *Journal of Atmospheric and Oceanic Technology* **25**: 519–533.

Marshak A, Platnick S, Varnai T, Wen G, Cahalan RF. 2006. Impact of three-dimensional radiative effects on satellite retrievals of cloud droplet sizes. *Journal of Geophysical Research* **111**: D09207.

Martin RV, Chance K, Jacob DJ, Kurosu TP, Spurr RJD, Bucsela E, Gleason JF, Palmer PI, Bey I, Fiore AM, Li Q, Yantosca RM, Koelemeijer RBA. 2002. An improved retrieval of tropospheric nitrogen dioxide from GOME. *Journal of Geophysical Research* **107**: 4437.

Martonchik JV, Kahn RA, Diner DJ. 2009. Retrieval of aerosol properties over land using MISR observations. In *Satellite Aerosol Remote Sensing Over Land*, Kokhanovsky AA, de Leeuw G (eds). Springer: Berlin; 267–291.

Masuda K, Ishimoto H, Takashima T. 2002. Retrieval of cirrus optical thickness and ice-shape information using total and polarized reflectance from satellite measurements. *Journal of Quantitative Spectroscopy and Radiative Transfer* **75**: 39–51.

Masunaga H, Kummerow CD. 2005. Combined radar and radiometer analysis of precipitation profiles for a parametric retrieval algorithm. *Journal of Atmospheric and Oceanic Technology* **22**: 909–929.

Maurellis AN, Lang R, van der Zande WJ, Aben I, Ubachs W. 2000. Precipitable water vapor column retrieval from GOME data. *Geophysical Research Letters* **27**: 903–906.

May DA. 1993. *Global and regional comparative performance of linear and non-linear satellite multichannel sea surface temperature algorithms*. Technical Report NRL/MR/7240-93-7049, Naval Research Laboratory: Stennis Space Center, MS; 36 pp.

Meissner T, Smith D, Wentz F. 2001. A 10 year intercomparison between collocated special sensor Microwave Imager oceanic surface wind speed retrievals and global analyses. *Journal of Geophysical Research* **106**: 11731–11742.

Menz G, Zock A. 1997. Regionalization of precipitation models in east Africa using Meteosat data. *International Journal of Climatology* **17**: 1011–1027.

Menzel WP. 2001. Cloud tracking with satellite imagery: from the pioneering work of Ted Fujita to the present. *Bulletin of the American Meteorological Society* **82**: 33–47.

Menzel WP, Baum BA, Strabala KI, Frey RA. 2002. *Cloud Top Properties and Cloud Phase Algorithm Theoretical Basis Document*, Theoretical Basis Document ATBD MOD-04. Cooperative Institute for Meteorological Satellite Studies, University of Wisconsin: Madison, WI; 61 pp.

Menzel WP, Frey RA, Zhang H, Wylie DP, Moeller CC, Holz RE, Maddux B, Baum BA, Strabala KI, Gumley LE. 2008. MODIS global cloud-top pressure and amount estimation: algorithm description and results. *Journal of Applied Meteorology and Climatology* **47**: 1175–1198.

Menzel WP, Holt FC, Schmit TJ, Aune RM, Schreiner AJ, Wade GS, Gray DG. 1998. Application of GOES-8/9 soundings to weather forecasting and nowcasting. *Bulletin of the American Meteorological Society* **79**: 2059–2077.

Menzel WP, Purdom JFW. 1994. Introducing GOES-I: The first of a new generation of geostationary operational environmental satellites. *Bulletin of the Amererican Meteorological Society* **75**: 757–781.

Menzel WP, Smith WL, Stewart TR. 1983. Improved cloud motion wind vector and altitude assignment using VAS. *Journal of Applied Meteorology and Climatology* **22**: 377–384.

Menzel WP, Wylie DP, Strabala KI. 1992. Seasonal and diurnal changes in cirrus clouds as seen in four years of observations with the VAS. *Journal of Applied Meteorology* **31**: 370–385.

Merchant CJ, Harris AR, Maturi E, Embury O, MacCallum SN, Mittaz J, Old CP. 2009. Sea surface temperature estimation from the Geostationary Operational Environmental Satellite-12 (GOES-12). *Journal of Atmospheric and Oceanic Technology* **26**: 570–581.

Merk C, Cermak J, Bendix J. 2010. Retrievals of optical and microphysical cloud properties from Meteosat SEVIRI data at night – a feasibility study based on radiative transfer calculations. *Remote Sensing Letters* **2**: 357–366.

Miller SW, Arkin PA, Joyce R. 2001a. A combined microwave/infrared rain rate algorithm. *International Journal of Remote Sensing* **22**: 3285–3307.

Miller SD, Stephens GL, Austin RT. 2001b. GOES 10 cloud optical property retrievals in the context of vertically varying microphysics. *Journal of Geophysical Research* **106**: 17981–17995.

Miller SW, Emery WJ. 1997. An automated neural network cloud classifier for use over land and ocean surfaces. *Journal of Applied Meteorology* **36**: 1346–1362.

Milz M, von Clarmann T, Fischer H, Glatthor N, Grabowski U, Höpfner M, Kellmann S, Kiefer M, Linden A, Mengistu Tsidu G, Steck T, Stiller GP. 2005. Water vapor distributions measured with the Michelson Interferometer for Passive Atmospheric Sounding on board Envisat (MIPAS/Envisat). *Journal of Geophysical Research* **110**: D24307.

Minnis P, Garber DP, Young DF, Arduini RF, Takano Y. 1998. Parameterizations of reflectance and effective emittance for satellite remote sensing of cloud properties. *Journal of Atmospheric Science* **55**: 3313–3339.

Minnis P, Heck PW, Young DF. 1992a. Inference of cirrus cloud properties using satellite-observed visible and infrared radiances, part II, verification of theoretical cirrus radiative properties. *Journal of the Atmospheric Sciences* **50**: 1305–1322.

Minnis P, Heck PW, Young DF, Fairall CW, Snider JB. 1992b. Stratocumulus cloud properties derived from simultaneous satellite and island-based instrumentation during FIRE. *Journal of Applied Meteorology* **31**: 317–339.

Minnis P, Smith WL, Jr, Young DF, Nguyen L, Rapp AD, Heck PW, Khaiyer MM. 2002. Near-real-time retrieval of cloud properties over the ARM CART area from GOES data. Proceedings of 12th Atmospheric Radiation Measurement Science Team Meeting: St. Petersburg, FL, 8–12 Apr 2002. US Department of Energy, Office of Energy Research, Office of Health and Environmental Research, Environmental Sciences Division: Washington, DC.

Mishchenko MI, Geogdzhayev IV, Cairns B, Carlson BE, Chowdhary J, Lacis AA, Liu L, Rossow WB, Travis LD. 2007. Past, present, and future of global aerosol climatologies derived from satellite observations: a perspective. *Journal of Quantitative Spectroscopy and Radiative Transfer* **106**: 325–347.

Mishchenko MI, Geogdzhayev IV, Cairns B, Rossow WB, Lacis A. 1999. Aerosol retrievals over the oceans by use of channels 1 and 2 AVHRR data: sensitivity analysis and preliminary results. *Applied Optics* **38**: 7325–7341.

Mitrescu C, L'Ecuyer T, Haynes J, Miller S, Turk J. 2010. CloudSat precipitation profiling algorithm – model description. *Journal of Applied Meteorology and Climatology* **49**: 991–1003.

Moore RK, Jones WL. 2004. Satellite scatterometer wind vector measurement – the legacy of the Seasat satellite scatterometer. *IEEE Geoscience and Remote Sensing Newsletter* **132**: 18–32.

Moroney C, Davies R, Muller JP. 2002. Operational retrieval of cloud-top heights using MISR data. *IEEE Transactions on Geoscience and Remote Sensing* **40**: 1532–1540.

Moula M, Verdebout J, Eva H. 2002. Aerosol optical thickness retrieval over the Atlantic Ocean using GOES imager data. *Physics and Chemistry of the Earth* **27**: 1525–1531.

Moulin C, Lambert CE, Dulac F, Dayan U. 1997. Control of atmospheric export of dust from North Africa by the North Atlantic oscillation. *Nature* **387**: 691–694.

Muller JP, Mandanayake A, Moroney C, Davies R, Diner DJ, Paradise S. 2002. MISR stereoscopic image matchers: techniques and

results. *IEEE Transactions on Geoscience and Remote Sensing* **40**: 1547–1559.
Munro R, Siddans R, Reburn WJ, Kerridge B. 1998. Direct measurement of tropospheric ozone from space. *Nature* **392**: 168–171.
Muth C, Lee PS, Shiue JC, Allan Webb W. 2004. Advanced technology microwave sounder on NPOESS and NPP. *Proceedings of Geoscience and Remote Sensing Symposium IGARSS'04 (IEEE)*, 20–24 September 2004, Anchorage, AK, Vol. 4; 2454–2458.
Nakajima T, King M. 1990. Determination of the optical thickness and effective particle radius of clouds from reflected solar radiation measurements. Part I: theory. *Journal of the Atmospheric Sciences* **47**: 1878–1893.
Nakajima TY, King MD, Spinhirne JD. 1991. Determination of the optical thickness and effective particle radius of clouds from reflected solar radiation measurements, part II, Marine stratocumulus observations. *Journal of the Atmospheric Sciences* **8**: 728–750.
Nakajima TY, Nakajima T. 1995. Wide-area determination of cloud microphysical properties from NOAA AVHRR measurements for FIRE and ASTEX regions. *Journal of the Atmospheric Sciences* **52**: 4043–4059.
Nakajima H, Suzuki M, Matsuzaki A, Ishigaki T, Waragai K, Mogi Y, Kimura N, Araki N, Yokota T, Kanzawa H, Sugita T, Sasano Y. 2002. Characteristics and performance of the Improved Limb Atmospheric Spectrometer (ILAS) in orbit. *Journal of Geophysical Research* **107**: 8213.
Nakamura K, Oki R, Iguchi T, Kojima M. 2005. Global precipitation measurement (GPM) mission and dual-frequency precipitation radar (DPR). *Proceedings of the SPIE* **5978**: 597806.
Nasiri SL, Baum BA. 2004. Daytime multilayered cloud detection using multispectral imager data. *Journal of Atmospheric and Oceanic Technology* **21**: 1145–1155.
Nauss T, Kokhanovsky AA. 2006. Discriminating raining from non-raining clouds in mid-latitudes using multispectral satellite data. *Atmospheric Chemistry and Physics* **6**: 5031–5036.
Nauss T, Kokhanovsky AA. 2007. Assignment of rainfall confidence values using multispectral satellite data at mid-latitudes: first results. *Advances in Geosciences* **10**: 99–102.
Negri AJ, Adler RF, Wetzel JP. 1984. Rain estimation from satellites: an examination of the Griffith-Woodley technique. *Journal of Applied Meteorology and Climatology* **23**: 102–116.
Nett H, Frerick J, Paulsen T, Levrini G. 2001. The atmospheric instruments and their applications: GOMOS, MIPAS and SCIAMACHY. *ESA Bulletin* **106**: 77–87.
Nielsen SN, Long DG. 2009. A wind and rain backscatter model derived from AMSR and SeaWinds data. *IEEE Transactions on Geoscience and Remote Sensing* **47**: 1595–1606.
Nieman SJ, Menzel WP, Hayden CM, Gray D, Wanzong ST, Velden CS, Daniels J. 1997. Fully automated cloud-drift winds in NESDIS operations. *Bulletin of the American Meteorological Society* **78**: 1121–1133.
Njoku EG, Barnett TP, Laurs RM, Vastano AC. 1985. Advances in satellite sea surface temperature measurements and oceanographic applications. *Journal of Geophysical Research* **90**: 11573–11586.
Njoku EG, Jackson TJ, Lakshmi V, Chan TK, Nghiem SV. 2003. Soil moisture retrieval from AMSR-E. *IEEE Transactions on Geoscience and Remote Sensing* **41**: 215–229.
Noel S, Buchwitz M, Bovensmann H, Burrows JP. 2005. Validation of SCIAMACHY AMC-DOAS water vapour columns. *Atmospheric Chemistry and Physics* **5**: 1835–1841.
Noel S, Buchwitz M, Bovensmann H, Hoogen R, Burrows JP. 1999. Atmospheric water vapor amounts retrieved from GOME satellite data. *Geophysical Research Letters* **26**: 1841–1844.
Noel S, Buchwitz M, Burrows JP. 2004. First retrieval of global water vapour column amounts from SCIAMACHY measurements. *Atmospheric Chemistry and Physics* **4**: 111–125.
Noel S, Mieruch S, Bovensmann H, Burrows JP. 2008. Preliminary results of GOME-2 water vapour retrievals and first applications in polar regions. *Atmospheric Chemistry and Physics* **8**: 1519–1529.
Noh YJ, Liu G, Seo EK, Wang JR. 2006. Development of a snowfall retrieval algorithm at high microwave frequencies. *Journal of Geophysical Research* **111**: D22216.
North P, Briggs S, Plummer S, Settle J. 1999. Retrieval of land surface bidirectional reflectance and aerosol opacity from ATSR-2 multiangle imagery. *IEEE Transactions on Geoscience and Remote Sensing* **37**: 526–537.
O'Carroll AG, Watts JG, Horrocks LA, Saunders RW, Rayner NA. 2006. Validation of the AATSR meteo product sea surface temperature. *Journal of Atmospheric and Oceanic Technology* **23**: 711–726.
Okamura Y, Tanaka K, Amano T, Hiramatsu M, Shiratama K. 2008. *Proceedings of 7th International Conference on Space Optics*, Toulouse, France, 14–17 October 2008. CNES/CTA: Toulouse/Blagnac.
Olson WS, Kummerow CD, Heymsfield GM, Giglio L. 1996. A method for combined passive-active microwave retrievals of cloud and precipitation profiles. *Journal of Applied Meteorology* **35**: 1763–1789.
Olson WS, Kummerow CD, Yang S, Petty GW, Tao WK, Bell TL, Braun SA, Wang Y, Lang SE, Johnson DE, Chin C. 2006. Precipitation and latent heating distributions from satellite passive microwave radiometry. Part I: improved method and uncertainties. *Journal of Applied Meteorology and Climatology* **45**: 702–720.
O'Sullivan F, Wash CH, Stewart M, Motell CE. 1990. Rain estimation from infrared and visible GOES satellite data. *Journal of Applied Meteorology* **29**: 209–223.
Ouaidrari H, Gowarda SN, Czajkowskib KP, Sobrinoc JA, Vermotea E. 2002. Land surface temperature estimation from AVHRR thermal infrared measurements an assessment for the AVHRR Land Pathfinder II data set. *Remote Sensing of Environment* **81**: 114–128.
Pairman D, Kittler J. 1986. Clustering algorithms for use with images of clouds. *International Journal of Remote Sensing* **7**: 855–866.
Palmer PI, Jacob DJ, Fiore AM, Martin RV, Chance K, Kurosu TP. 2003. Mapping isoprene emissions over North America using formaldehyde column observations from space. *Journal of Geophysical Research* **108**: 4180.
Pan L, Gille JC, Edwards DP, Bailey PL, Rodgers CD. 1998. Retrieval of tropospheric carbon monoxide for the mopitt experiment. *Journal of Geophysical Research* **103**: 32277–32290.
Pankiewicz GS. 1995. Pattern recognition techniques for identification of cloud and cloud systems. *Meteorological Applications* **2**: 257–271.
Park M, Randel WJ, Kinnison DE, Garcia RR, Choi W. 2004. Seasonal variation of methane, water vapor, and nitrogen oxides near the tropopause: satellite observations and model simulations. *Journal of Geophysical Research* **109**: D03302.
Parkinson CL. 2003. Aqua: an earth-observing satellite mission to examine water and other climate variables. *IEEE Transactions on Geoscience and Remote Sensing* **41**: 173–183.
Pavolonis MJ, Heidinger AK. 2004. Daytime Cloud Overlap Detection from AVHRR and VIIRS. *J. Appl. Meteorol.* **43**: 762–778.
Penner JE, Quaas J, Storelvmo T, Takemura T, Boucher O, Guo H, Kirkevag A, Kristjánsson JE, Seland Ø. 2006. Model intercomparison of indirect aerosol effects. *Atmospheric Chemistry and Physics* **6**: 3391–3405.
Perez JC, Herrera F, Rosa F, González A, Wetzel MA, Borys RD, Lowenthal DH. 2000. Retrieval of marine stratus cloud droplet size from NOAA AVHRR night-time imagery. *Remote Sensing of Environment* **73**: 31–45.
Pessi AT, Businger S. 2009. Relationships among lightning, precipitation, and hydrometeor characteristics over the North Pacific Ocean. *Journal of Applied Meteorology and Climatology* **48**: 833–848.
Petty GW. 1990. *On the response of the special sensor microwave/imager to the marine environment – implications for atmospheric parameter retrievals*, PhD thesis, University of Washington: Seattle, WA; 118 pp.
Petty GW. 1995. The status of satellite-based rainfall estimation over land. *Remote Sensing of Environment* **51**: 125–137.
Peyridieu S, Chedin A, Tanre D, Capelle V, Pierangelo C, Lamquin N, Armante R. 2010. Saharan dust infrared optical depth and altitude retrieved from AIRS: a focus over North Atlantic-comparison to MODIS and CALIPSO. *Atmospheric Chemistry and Physics* **10**: 1953–1967.
Phulpin T, Derrien M, Brard A. 1983. A two-dimensional histogram procedure to analyze cloud cover from NOAA satellite high resolution imagery. *Journal of Climate and Applied Meteorology* **22**: 1332–1345.
Pierangelo C, Mishchenko M, Balkanski Y, Chedin A. 2005. Retrieving the effective radius of Saharan dust coarse mode from AIRS. *Geophys. Res. Lett.* **32**: L20813.
Planet WG, Lienesch JH, Miller AJ, Nagatani R, Mcpeters RD, Hilsenrath E, Cebula RP, Deland MT, Wellemeyer CG, Horvath K. 1994. Northern-hemisphere total ozone values from 1989–1993 determined with the NOAA-11 Solar Backscatter Ultraviolet (SBUV/2) instrument. *Geophys. Res. Lett.* **21**: 205–208.
Platnick S, King MD, Ackerman SA, Menzel WP, Baum BA, Riédi JC, Frey RA. 2003. The MODIS cloud products: algorithms and examples from Terra. *IEEE Transactions on Geoscience and Remote Sensing* **41**: 459–473.

Platt U. 1994. Differential optical absorption spectroscopy (DOAS). *Monitoring by Spectroscopic Techniques*, John Wiley & Sons: New York, NY; 27–84.

Platt CMR, Stephens GL. 1980. The interpretation of remotely sensed high cloud emittances. *Journal of Atmospheric Sciences* **37**: 2314–2322.

Pompei A, Marrocu M, Boi P, Dalu G. 1995. Validation of retrieval algorithms for the infrared remote sensing of precipitation with the Sardinian gauge network data. *Nuovo Cimento* **18**: 483–496.

Prata AJ. 1994a. Land surface temperatures derived from the advanced very high resolution radiometer and the along-track scanning radiometer 2: experimental results and validation of AVHRR algorithms. *Journal of Geophysical Research* **99**: 13025–13058.

Prata AJ. 1994b. Land surface determination from satellites. *Advances in Space Research* **14**: 315–326.

Prata AJ, Bernardo C. 2007. Retrieval of volcanic SO2 column abundance from atmospheric infrared sounder data. *Journal of Geophysical Research* **112**: D20204.

Prata AJ, Carn SA, Stohl A, Kerkmann J. 2007. Long range transport and fate of a stratospheric volcanic cloud from Soufrie're Hills volcano, Montserrat. *Atmospheric Chemistry and Physics* **7**: 5093–5103.

Prata AJ, Cechet RP. 1999. An assessment of the accuracy of land surface temperature determination from the GMS-5 VISSR. *Remote Sensing of Environment* **67**: 1–14.

Prata AJ, Kerkmann J. 2007. Simultaneous retrieval of volcanic ash and SO2 using MSG-SEVIRI measurements. *Geophysical Research Letters* **34**: L05813.

Prata AJ, Self S, Rose WI, O'Brien DM. 2003. Global, longterm sulphur dioxide measurements from TOVS data: a new tool for studying explosive volcanism and climate. In *Volcanism and the Earth's Atmosphere*, *Geophysical Monograph Series, Vol. 139*, Robock A, Oppenheimer C (eds). AGU: Washington, DC; 75–92.

Prunet P, Thépaut JN, Cassé V. 1998. The information content of clear sky IASI radiances and their potential for numerical weather prediction. *Quarterly Journal of the Royal Meteorological Society* **124**: 211–241.

Pukite J, Kühl S, Deutschmann T, Wilms-Grabe W, Friedeburg C, Platt U, Wagner T. 2006. Retrieval of stratospheric trace gases from SCIAMACHY limb measurements. *Proceedings of the First Atmospheric Science Conference*, Frascati, Italy, 8–12 May 2006. ESA/ESRIN: Frascati.

Pumphrey HC, Filipiak MJ, Livesey NJ, Schwartz MJ, Boone C, Walker KA, Bernath P, Ricaud P, Barret B, Clerbaux C, Jarnot RF, Manney GL, Waters JW. 2007. Validation of middle-atmosphere carbon monoxide retrievals from Microwave Limb Sounder on Aura. *Journal of Geophysical Research* **112**: D24S38.

Rahnama P, Rochon YJ, McDade IC, Shepherd GG, Gault WA, Scott A. 2006. Satellite measurement of stratospheric winds and ozone using Doppler Michelson Interferometry. Part I: instrument model and measurement simulation. *Journal of Atmospheric and Oceanic Technology* **23**: 753–769.

Ramanathan V, Cess RD, Harrison EF, Minnis P, Barkstrom BR, Ahmed E, Hartmann D. 1989. Cloud-radiative forcing and climate: results from the Earth radiation budget experiment. *Science* **243**: 57–63.

Ramaswamy V, Boucher O, Haigh J, Hauglustaine D, Haywood J, Myhre G, Nakajima T, Shi GY, Solomon S, Betts R, Charlson R, Chuang C, Daniel JS, Del Genio A, van Dorland R, Feichter J, Fuglestvedt J, de Forster PM, Ghan SJ, Jones A, Kiehl JT, Koch D, Land C, Lean J, Lohmann U, Minschwaner K, Penner JE, Roberts DL, Rodhe H, Roelofs GJ, Rotstayn LD, Schneider TL, Schumann U, Schwartz SE, Schwarzkopf MD, Shine KP, Smith S, Stevenson DS, Stordal F, Tegen I, Zhang Y. 2001. Radiative forcing of climate change. In *Climate Change 2001: The Scientific Basis*, Houghton JT, Ding Y, Griggs DJ, Noguer M, van der Linden PJ, Dai X, Maskell K, Johnson CA (eds). Cambridge University Press: Cambridge, UK; 349–416.

Raspollini P, Belotti C, Burgess A, Carli B, Carlotti M, Ceccherini S, Dinelli BM, Dudhia A, Flaud JM, Funke B, Höpfner M, Lopez Puertas M, Payne V, Piccolo C, Remedios JJ, Ridolfi M, Spang R. 2006. MIPAS level 2 operational analysis. *Atmospheric Chemistry and Physics* **6**: 5605–5630.

Rast M, Bezy JL. 1999. The ESA medium resolution imaging spectrometer MERIS – A review of the instrument and its mission. *International Journal of Remote Sensing* **20**: 1681–1702.

Razavi A, Clerbaux C, Wespes C, Clarisse L, Hurtmans D, Payan S, Camy-Peyret C, Coheur PF. 2009. Characterization of methane retrievals from the IASI space-borne sounder. *Amtos. Chem. Physics* **9**: 7889–7899.

Remer LA, Kaufman YJ, Tanre D, Mattoo S, Chu DA, Martins JV, Li RR, Ichoku C, Levy RC, Kleidman RG, Eck TF, Vermote E, Holben BN. 2005. The MODIS aerosol algorithm, products and validation. *Journal of the Atmospheric Sciences* **62**: 947–973.

Remer LA, Kleidman RG, Levy RC, Kaufman YJ, Tanre D, Mattoo S, Martins JV, Ichoku C, Koren I, Yu H, Holben BN. 2007. Global aerosol climatology from the MODIS satellite sensors. *Journal of Geophysical Research* **113**: D14S07.

Reuter M, Thomas W, Albert P, Lockhoff M, Weber R, Karlsson KG, Fischer J. 2009. The CM-SAF and FUB cloud detection schemes for SEVIRI: validation with synoptic data and initial comparison with MODIS and CALIPSO. *Journal of Applied Meteorology and Climatology* **48**: 301–316.

Richter A, Burrows J. 2002. Retrieval of Tropospheric NO2 from GOME Measurements. *Adv. Space Res.* **29**: 1673–1683.

Richter A, Wittrock F, Burrows JP. 2006. SO2 measurements with SCIAMACHY. *Proceedings of Atmospheric Science Conference*, Frascati, Italy, 8–12 May 2006. ESRIN: Frascati.

Rodgers CD. 2000. *Inverse Methods for Atmospheric Sounding: Theory and Practice*. World Scientific Publishing: Hackensack, NJ.

Roebeling RA, Deneke HM, Feijt AJ. 2008. Validation of cloud liquid water path retrievals from SEVIRI using one year of CloudNET observations. *Journal of Applied Meteorology and Climatology* **47**: 206–222.

Roebeling RA, Feijt AJ, Stammes P. 2006. Cloud property retrievals for climate monitoring: Implications of differences between Spinning Enhanced Visible and Infrared Imager (SEVIRI) on METEOSAT-8 and Advanced Very High Resolution Radiometer (AVHRR) on NOAA-17. *J. Geophys. Res.* **111**: D20210.

Roebeling RA, Holleman I. 2009. SEVIRI rainfall retrieval and validation using weather radar observations. *Journal of Geophysical Research* **114**: D21202.

van Roozendael M, Loyola D, Spurr R, Balis D, Lambert JC, Livschitz Y, Valks P, Ruppert T, Kenter P, Fayt C, Zehner C. 2006. Ten years of GOME/ERS2 total ozone data: the new GOME Data Processor (GDP) version 4:I. Algorithm description. *Journal of Geophysical Research* **111**: D14311, DOI: 10.1029/2005JD006375.

Rosenfeld D, Lensky I. 1998. Satellite-based insights into precipitation formation processes in continental and maritime convective clouds. *Bulletin of the American Meteorological Society* **79**: 2457–2476.

Rosenkranz P. 2001. Retrieval of temperature and moisture profiles from AMSU-A and AMSU-B measurements. *IEEE Transactions on Geoscience and Remote Sensing* **39**: 2429–2435.

Ruff IS, Gruber A. 1988. *General determination of Earth surface type and cloud amount using multi-spectral AVHRR data*. NOAA Technical Report NESDIS 39, NOAA: Washington, DC; 30.

Santee ML, Lambert A, Read WG, Livesey NJ, Cofield RE, Cuddy DT, Daffer WH, Drouin BJ, Froidevaux L, Fuller RA, Jarnot RF, Knosp BW, Manney GL, Perun VS, Snyder WV, Stek PC, Thurstans RP, Wagner PA, Waters JW, Muscari G, de Zafra RL, Dibb JE, Fahey DW, Popp PJ, Marcy TP, Jucks KW, Toon GC, Stachnik RA, Bernath PF, Boone CD, Walker KA, Urban J, Murtagh D. 2007. Validation of the aura microwave limb sounder HNO3 measurements. *Journal of Geophysical Research* **112**: D24S40, DOI: 10.1029/2007JD008721.

Santee ML, Manney GL, Livesey NJ, Froidevaux L, Pumphrey HC, Read WG, Schwartz MJ, Waters JW. 2005. Polar processing and development of the 2004 Antarctic ozone hole: first results from Aura MLS. *Journal of Geophysical Research* **32**: L12817.

Santee ML, Manney GL, Livesey NJ, Read WG. 2004. Three-dimensional structure and evolution of stratospheric HNO3 based on UARS microwave limb sounder measurements. *Journal of Geophysical Research* **109**: D15306.

Santee ML, Read WG, Waters JW, Froidevaux L, Manney GL, Flower DA, Jarnot RF, Harwood RS, Peckham GE. 2009. Inter-hemispheric differences in polar stratospheric HNO_3, H_2O, ClO and O_3. *Science* **267**: 849–852.

Sasaki T, Nakagawa K. 2009. GCOM mission overview. *Transactions of Space Technology Japan* **7**: 21–25.

Saunders RW. 1986. An automated scheme for the removal of cloud contamination from AVHRR radiances over western Europe. *International Journal of Remote Sensing* **7**: 867–886.

Saunders RW, Kriebel KT. 1988. An improved method for detecting clear sky and cloudy radiances from AVHRR data. *International Journal of Remote Sensing* **9**: 123–150.

Schlüssel P, Accadia C, Munro R, Phillips P, Stoffelen A. 2009. Sounding requirements for the future EUMETSAT polar system.

Proceedings of the 8th International Symposium on Tropospheric Profiling, 19–23 October 2009, Delft.
Schlüssel P, Emery W. 1990. Atmospheric water vapour over oceans from SSM/I measurements. *International Journal of Remote Sensing* **11**: 753–766.
Schmetz J. 1989. Towards a surface radiation climatology. Retrieval of downward irradiance from satellites. *Atmospheric Research* **23**: 287–321.
Schmetz J, Holmlund K, Hoffman J, Strauss B, Mason B, Gartner V, Koch A, van de Berg L. 1993. Operational cloud-motion winds from Meteosat infrared images. *Journal of Applied Meteorology* **32**: 1206–1225.
Schmetz J, Pili P, Tjemkes S, Just D, Kerkmann J, Rota S, Ratier A. 2002. An introduction to Meteosat Second Generation (MSG). *Bulletin of the American Meteorological Society* **83**: 977–992.
Schmit TJ, Feltz WF, Menzel WP, Jung J, Noel AP, Heil JN, Nelson JP, Wade GS. 2002. Validation and use of GOES sounder moisture information. *Weather and Forecasting* **17**: 139–154.
Schmidt GA, Hoffmann G, Shindell DT, Hu Y. 2005. Modelling atmospheric stable water isotopologues and the potential for constraining cloud processes and stratosphere-troposphere water exchange. *Journal of Geophysical Research* **110**: D21.
Schmülling F, Zerfowski I, Pillukat A, Bonsignori R. 2010. METimage: a multispectral imaging radiometer for the EUMETSAT Polar System follow-on satellite mission. *Proceedings of the SPIE* **7826**: 78260P, DOI: 10.1117/12.869272.
Schneider M, Hase F, Blumenstock T. 2006. Ground-based remote sensing of HDO/H2O ratio profiles: introduction and validation of an innovative retrieval approach. *Atmospheric Chemistry and Physics* **6**: 4705–4722.
Schneising O, Buchwitz M, Burrows JP, Bovensmann H, Reuter M, Notholt J, Macatangay R, Warneke T. 2008. Three years of greenhouse gas column averaged dry air mole fractions retrieved from satellite -Part 1: carbon dioxide. *Atmospheric Chemistry and Physics* **8**: 3827–3853.
Schnetzler CC, Bluth GSJ, Krueger AJ, Walter LS. 1997. A proposed volcanic sulfur dioxide index (VSI). *Journal of Geophysical Research* **102**: 20087–20092.
Schoeberl MR, Douglass AR, Hilsenrath E, Bhartia PK, Beer R, Waters JW, Gunson MR, Froidevaux L, Gille JC, Barnett JJ, Levelt PF, de Cola P. 2006. Overview of the EOS aura mission. *IEEE Transactions on Geoscience and Remote Sensing* **44**: 1066–1074.
Schueler CF, Barnes WL. 1998. Next-generation MODIS for polar operational environmental satellites. *Journal of Atmospheric and Oceanic Technology* **15**: 430–439.
Schutgens NAJ. 2008. Simulating range oversampled Doppler Radar profiles of inhomogeneous targets. *Journal of Atmospheric and Oceanic Technology* **25**: 1514–1528.
Scofield RA, Kuligowski RJ. 2003. Status and outlook of operational satellite precipitation algorithms for extreme precipitation events. *Weather and Forecasting* **18**: 1037–1051.
Seddon AM, Hunt GE. 1985. Segmentation of clouds using cluster analysis. *International Journal of Remote Sensing* **10**: 717–731.
Seemann S, Li J, Menzel WP, Gumley L. 2003. Operational retrieval of atmospheric temperature, moisture, and ozone from MODIS infrared radiances. *Journal of Applied Meteorology* **42**: 1072–1091.
Shepherd GG, McDade IC, Gault WA, Rochon YJ, Scott A, Rowlands N, Buttner G. 2001. The stratospheric wind interferometer for transport studies (SWIFT). *Advances in Space Research* **27**: 1071–1079.
Shi L. 2001. Retrieval of atmospheric temperature profiles from AMSU-A measurements using a neural network approach. *Journal of Atmospheric and Oceanic Technology* **18**: 340–347.
Shibata A. 2006. A wind speed retrieval algorithm by combining 6 and 10 GHz data from advanced microwave scanning radiometer: wind speed inside hurricanes. *Journal of Oceanography* **62**: 351–359.
Silvestrin P, Bagge R, Bonnedal M, Carlstrom A, Christensen J, Hagg M, Lindgren T, Zangerl F. 2000. Spaceborne GNSS radio occultation instrument for operational applications. *Proceeding of the 13th International Technical Meeting of the Satellite Division of the Institute of Navigation ION GPS*, Salt Lake City, UT, 19–22 September 2000. ION GPS: Manassas, VA.
Simmer C, Raschke E, Ruprecht E. 1982. A method for determination of cloud properties from two-dimensional histograms. *Annalen der Meteorologie* **8**: 130–132.
Singh D, Bhatia RC. 2008. Development of a neural network algorithm for the retrieval of TPW from NOAA16 AMSU measurements. *International Journal of Remote Sensing* **29**: 4045–4060.
Skofronick-Jackson G, Kim MJ, Weinman JA, Chang DE. 2004. A physical model to determine snowfall over land by microwave radiometry. *IEEE Transactions on Geoscience and Remote Sensing* **42**: 1047–1058.
Smith WL. 1983. The retrieval of atmospheric profiles from VAS geostationary radiance observations. *Journal of the Atmospheric Sciences* **40**: 2025–2035.
Smith E, Asrar G, Furuhama Y, Ginati A, Kummerow C, Levizzani V, Mugnai A, Nakamura K, Adler R, Casse V, Cleave M, Debois M, Durning J, Entin J, Houser P, Iguchi T, Kakar R, Kaye J, Kojima M, Lettenmaier DP, Luther M, Mehta A, Morel P, Nakazawa T, Neeck S, Okamoto K, Oki R, Raju G, Shepherd M, Stocker E, Testud J, Wood EF. 2007. The international global precipitation measurement (GPM) program and mission: an overview. In *Measuring Precipitation from Space: EURAINSAT and the Future*, Levizzani V, Turk FJ (eds). Kluwer Academic Publishers: Norwell; 722 pp.
Smith WL, Bishop WP, Dvorak VF, Hayden CM, McElroy JH, Mosher FR, Oliver VJ, Purdom JF, Wark DQ. 1986. The meteorological satellite: overview of 25 years of operation. *Science* **231**: 455–62.
Smith WL Jr, Minnis P, Finney H, Palikonda R, Khaiyer MM. 2008. An evaluation of operational GOES-derived single-layer cloud top heights with ARSCL data over the ARM Southern Great Plains site. *Geophysical Research Letters* **35**: L13820.
Smith WL, Platt CMR. 1978. Comparison of satellite deduced cloud heights with indications from radiosonde and ground-based laser measurements. *Journal of Applied Meteorology* **17**: 1796–1802.
Sobrino JA, Li ZL, Stoll MP, Becker F. 1996. Multi-channel and multi-angle algorithms for estimating sea and land surface temperature with ATSR data. *International Journal of Remote Sensing* **17**: 2089–2114.
Sobrino JA, Romaguera M. 2004. Land surface temperature retrieval from MSG1-SEVIRI data. *Remote Sensing of Environment* **92**: 247–254.
Soden BJ, Bretherton FP. 1994. Evaluation of water vapor distribution in general circulation models using satellite observations. *Journal of Geophysical Research* **99**: 1187–1210.
Sohn BJ, Smith EA. 2003. Explaining sources of discrepancy in SSM/I waer vapor algorithms. *Journal of Climate* **16**: 3229–3255.
Sorooshian S, Hsu KL, Gao X, Gupta HV, Imam B, Braithwaite D. 2000. Evaluation of PERSIANN system satellite-based estimates of tropical rainfall. *Bulletin of the American Meteorological Society* **81**: 2035–2046.
Spurr R, Loyola D, Thomas W, Balzer W, Mikusch E, Aberle B, Slijkluis S, Ruppert T, van Roozendael M, Lambert JC, Soebijanta T. 2005. GOME level 1-to-2 data processor version 3.0: a major upgrade of the GOME/ERS-2 total ozone retrieval algorithm. *Applied Optics* **44**: 7196–7209.
Staelin D, Kunyi K, Pettyjohn R, Poon K, Wilcox R, Waters J. 1976. Remote sensing of atmospheric water vapor and liquid water with the Nimbus 5 microwave spectrometer. *Journal of Applied Meteorology* **15**: 1204–1214.
Stengel M, Reuter M, Preusker R, Fischer J, Bennartz R. 2005. Remote sensing of vertical integrated water vapor using SEVIRI infrared measurements. *Proceedings of the 2005 EUMETSAT Meteorological Satellite Conference*, Dubrovnik, Croatia, 19–23 September 2005. EUMETSAT: Darmstadt; 504–506.
Stephens GL, Kummerow CD. 2007. The remote sensing of clouds and precipitation from space: a review. *Journal of the Atmospheric Sciences* **64**: 3742–3765.
Stephens GL, Vane DG, Boain RJ, Mace GG, Sassen K, Wang Z, Illingworth AJ, O'Connor EJ, Rossow WB, Durden SL, Miller SD, Austin RT, Benedetti A, Mitrescu C, CloudSat Science Team T. 2002. The CLOUDSAT mission and the A-TRAIN. *Bulletin of the American Meteorological Society* **83**: 1771–1790.
Stephens GL, Vane DG, Tanelli S, Im E, Durden S, Rokey M, Reinke D, Partain P, Mace GG, Austin R, L'Ecuyer T, Haynes J, Lebsock M, Suzuki K, Waliser D, Wu D, Kay J, Gettelman A, Wang Z, Marchand R. 2008. CloudSat mission: performance and early science after the first year of operation. *Journal of Geophysical Research* **113**: D00A18.
Stewart TR, Hayden CM, Smith WL. 1985. A note on water-vapor wind tracking using VAS data on McIDAS. *Bulletin of the American Meteorological Society* **66**: 1111–1115.
Stiller GP, Tsidu GM, von Clarmann T, Glatthor N, Höpfner M, Kellmann S, Linden A, Ruhnke R, Fischer H. 2003. An enhanced HNO3 second maximum in the Antarctic midwinter upper stratosphere. *Journal of Geophysical Research* **110**: D20303.

Stoffelen A, Pailleux J, Käallen E, Vaughan JM, Isaksen L, Flamant P, Wergen W, Andersson E, Schyberg H, Culoma A, Meynart R, Endemann M, Ingmann P. 2005. The atmospheric dynamics mission for global wind field measurement. *Bulletin of the American Meteorological Society* **86**: 73–87.

Stogryn AP, Butler CT, Bartolac TJ. 1994. Ocean surface wind retrievals from special sensor microwave imager data with neural networks. *Journal of Geophysical Research* **99**: 981–984.

Stolarski RS, Bloomfield P, McPeters RD, Herman JR. 1991. Total ozone trends deduced from Nimbus 7 TOMS data. *Geophysical Research Letters* **18**: 1015–1018.

Stolarski RS, Labow GJ, McPeters RD. 1997. Springtime Antarctic total ozone measurements in the early-1970s from the BUV instrument on Nimbus 4. *Geophysical Research Letters* **24**: 591–594.

Stowe LL, Davis PA, McClain EP. 1999. Scientific basis and initial evaluation of the CLAVR-1 global clear/cloud classification algorithm for the advanced very high resolution radiometer. *Journal of Atmospheric and Oceanic Technology* **16**: 656–681.

Stowe LL, Ignatov AM, Singh RR. 1997. Development, validation and potential enhancements to the second generation operational aerosol product at NOAA/NESDIS. *Journal of Geophysical Research* **102**: 16923–16934.

Stowe LL, McClain EP, Carey R, Pellegrino P, Gutman G, Davis P, Long C, Hart S. 1991. Global distribution of cloud cover derived from NOAA/AVHRR operational satellite data. *Advances in Space Research* **11**: 51–54.

Strabala KI, Ackerman SA, Menzel WP. 1994. Cloud properties inferred from 8–12 Am data. *Journal of Applied Meteorology* **33**: 212–229.

Strong M, Scharp ZD, Gutzler DS. 2007. Diagnosing moisture transport using D/H ratios of water vapor. *Geophysical Research Letters* **34**: L03404.

Strow LL, Hannon SE. 2008. A 4-year zonal climatology of lower tropospheric CO2 derived from ocean-only atmospheric infrared sounder observations. *Journal of Geophysical Research* **113**: D18302.

Strow LL, Hannon SE, Machado S, Motteler H, Tobin D. 2003. An overview of the AIRS radiative transfer model. *IEEE Transactions on Geoscience and Remote Sensing* **41**: 303–313.

Stubenrauch CJ, Chedin A, Radel G, Scott NA, Serrar S. 2006. Cloud properties and their seasonal and diurnal variability from TOVS Path-B. *J. Climate* **19**: 5531–5553.

Stubenrauch CJ, Cros S, Guignard A, Lamquin N. 2010. A 6-year global cloud climatology from the Atmospheric InfraRed Sounder AIRS and a statistical analysis in synergy with CALIPSO and CloudSat. *Atmospheric Chemistry and Physics* **10**: 7197–7214.

Stubenrauch CJ, Cros S, Lamquin N, Armante R, Chedin A, Crevoisier C, Scott NA. 2008. Cloud properties from AIRS and evaluation with CALIPSO. *Journal of Geophysical Research* **113**: D00A10.

Stubenrauch CJ, Rossow WB, Scott NA, Chedin A. 1999. Clouds as seen by Infrared Sounders (3I) and Imagers (ISCCP). Part III: spatial heterogeneity and radiative effects. *Journal of Climate* **12**: 3419–3442.

Stuhlmann R, Rodriguez A, Tjemkes S, Grandell J, Arriaga A, Bézy JL, Aminou D, Bensi P. 2005. Plans for EUMETSAT's third generation meteosat geostationary satellite programme. *Advances in Space Research* **36**: 975–981.

Sun F, Goldberg MD, Liu X, Bates JJ. 2010. Estimation of outgoing long wave radiation from atmospheric infrared sounder radiance measurements. *Journal of Geophysical Research* **115**: D09103.

Sun D, Pinker RT. 2003. Estimation of land surface temperature from a Geostationary Operational Environmental Satellite (GOES-8). *Journal of Geophysical Research* **108**: 4326.

Sun D, Pinker RT. 2007. Retrieval of surface temperature from the MSG-SEVIRI observations: Part I: methodology. *International Journal of Remote Sensing* **28**: 5255–5272.

Surussavadee C, Staelin DH. 2010. Global precipitation retrievals using the NOAA AMSU millimeter-wave channels: comparisons with rain gauges. *Journal of Applied Meteorology and Climatology* **49**: 124–135.

Susskind J, Barnet C, Blaisdell J. 2003. Retrieval of atmospheric and surface parameters from AIRS/AMSU/HSB data in the presence of clouds. *IEEE Transactions on Geoscience and Remote Sensing* **41**: 390–409.

Susskind J, Barnet C, Blaisdell J, Iredell L, Keita F, Kouvaris L, Molnar G, Chahine M. 2006. Accuracy of geophysical parameters derived from AIRS/AMSU as a function of fractional cloud cover. *Journal of Geophysical Research* **111**: D09S17.

Takahashi S, Taguchi M, Okano S, Fukunishi H, Kawamura H. 1992. Derivation of total ozone amounts over Japan from NOAA/TOYS data. *Journal of the Meteorological Society of Japan* **5**: 919–928.

Tamminen J, Kyrölä E, Sofieva VF, Laine M, Bertaux JL, Hauchecorne A, Dalaudier F, Fussen D, Vanhellemont F, Fanton-d'Andon O, Barrot G, Mangin A, Guirlet M, Blanot L, Fehr T, Saavedra de Miguel L, Fraisse R. 2010. GOMOS data characterisation and error estimation. *Atmospheric Chemistry and Physics* **10**: 9505–9519.

Tan DGH, Andersson E. 2005. Simulation of the yield and accuracy of wind profile measurements from the Atmospheric Dynamics Mission (ADM-Aeolus). *Quarterly Journal of the Royal Meteorological Society* **131**: 1737–1757.

Tanaka K, Okamura Y, Amano T, Hiramatsu M, Shiratama K. 2009. Development status of the Second-Generation Global Imager (SGLI) on GCOM-C. *Proceedings of the SPIE* **7474**: 74740N, DOI: 10.1117/12.830963.

Tang B, Bi Y, Li ZL, Xia J. 2008. Generalized split-window algorithm for estimate of land surface temperature from Chinese geostationary fengyun meteorological satellite (FY-2C) data. *Sensors* **8**: 933–951.

Tanré D. 2010. Derivation of tropospheric aerosol properties from satellite observations. *Comptes Rendus Geoscience* **342**: 403–411.

Tanré D, Kaufman YJ, Herman M, Mattoo S. 1997. Remote sensing of aerosol properties over oceans using the MODIS/EOS spectral radiances. *Journal of Geophysical Research* **102**: 16971–16988.

Tanskanen A, Krotkov NA, Herman JR, Arola A. 2006. Surface ultraviolet irradiance from OMI. *IEEE Transactions on Geoscience and Remote Sensing* **44**: 1267–1271.

Tanskanen A, Lindfors A, Maatta A, Krotkov N, Herman J, Kaurola J, Koskela T, Lakkala K, Fioletov V, Bernhard J, McHenzie R, Kondo Y, O'Neill M, Slaper H, den Outer P, Bais AF, Tamminen J. 2007. Validation of daily erythemal doses from OMI with ground-based UV measurement data. *Journal of Geophysical Research* **112**: D24S44.

Taylor VR. 1990. *Implementation of reflectance models in operational AVHRR radiation budget processing*. Technical Report NESDIS 49, NOAA: Washington, DC; 34 pp.

Taylor KE, Penner JE. 1994. Response of the climate system to atmospheric aerosols and greenhouse gases. *Nature* **369**: 734–737.

Thies B, Nauss T, Bendix J. 2008a. Delineation of raining from non-raining clouds during nighttime using Meteosat-8 data. *Meteorological Applications* **15**: 219–230.

Thies B, Nauss T, Bendix J. 2008b. Discriminating raining from nonraining cloud areas at mid-latitudes using meteosat second generation SEVIRI day-time data. *Atmospheric Chemistry and Physics* **8**: 1–9.

Thies B, Nauss T, Bendix J. 2008c. Precipitation process and rainfall intensity differentiation using meteosat second generation spinning enhanced visible and infrared imager data. *Journal of Geophysical Research* **113**: D23206.

Tian B, Shaikh MA, Azimi-Sadjadi MR, Vonder Haar TH, Reinke DL. 1999. A study of cloud classification with neural networks using spectral and textural features. *IEEE Transactions on Neural Networks* **10**: 138–151.

Tinel C, Testud J, Pelon J, Hogan RH, Protat A, Delanoe J, Bouniol D. 2005. The retrieval of ice cloud properties from cloud radar and lidar synergy. *Journal of Applied Meteorology* **44**: 860–875.

Todd MC, Barrett EC, Beaumont MJ, Bellerby TJ. 1999. Estimation of daily rainfall over the upper Nile river basin using a continuously calibrated satellite infrared technique. *Meteorological Applications* **6**: 201–210.

Todd MC, Kidd C, Kniveton D, Bellerby TJ. 2001. A combined satellite infrared and passive microwave technique for estimation of small-scale rainfall. *Journal of Atmospheric and Oceanic Technology* **18**: 742–755.

Tokuno M. 1996. Operational system for extracting cloud motion and water vapor motion winds from GMS-5 image data. *Proceedings of 3rd International Winds Workshop*, Ascona, CH, 10–12 June 1996. WMO: Geneva, CH.

Tomassini M, Kelly G, Saunders R. 1999. Use and impact of satellite atmospheric motion winds on ECMWF analyses and forecasts. *Mon. Weath. Rev.* **127**: 971–986.

Torres O, Bhartia PK, Herman JR, Sinyuk A, Ginoux P, Holben B. 2002. A long-term record of aerosol optical depth from TOMS observations and comparison to AERONET measurements. *Journal of the Atmospheric Sciences* **59**: 398–413.

Torres O, Tanskanen A, Veihelmann B, Ahn C, Braak R, Bhartia PK, Veefkind P, Levelt P. 2007. Aerosols and surface UV products from

ozone monitoring instrument observations: an overview. *Journal of Geophysical Research* **112**: D24S47.
Townshend JRG, Justice CO. 2002. Towards operational monitoring of terrestrial systems by moderate-resolution remote sensing. *Remote Sensing of Environment* **83**: 351–359.
Tran N, Remy F, Feng H, Femenias P. 2008. Snow facies over ice sheets derived from Envisat active and passive observations. *IEEE Transaction on Geoscience and Remote Sensing* **46**: 3694–3708.
Trigo IF, Peres LF, DaCamara CC, Freitis SC. 2008. Thermal land surface emissivity retrieved from SEVIRI/meteosat. *IEEE Transactions on Geoscience and Remote Sensing* **46**: 307–315.
Tsonis AA. 1987. Determining rainfall intensity and type from GOES imagery in the midlatitudes. *Remote Sensing of Environment* **21**: 29–36.
Tsonis AA, Isaac GA. 1985. On a new approach for instantaneous rain area delineation in the midlatitudes using GOES data. *Journal of Applied Meteorology and Climatology* **24**: 1208–1218.
Tukiainen S, Kyrölä E, Verronen PT, Fussen D, Blanot L, Barrot G, Hauchecorne A, Lloyd N. 2010. Retrieval of ozone profiles from GOMOS limb scattered measurements. *Atmospheric Measurement Techniques Discussions* **3**: 4355–4382.
Turk FJ, Ebert EE, Oh HJ, Sohn BJ, Levizzani V, Smith EA, Ferraro RR. 2003. Validation of an operational global precipitation analysis at short time scales. *Proceedings of 12th Conference on Satellite Meteorology and Oceanography*, Long Beach, CA, 9–13 February 2003. American Meteorological Society: Boston, MA; 1–21.
Turk FJ, Miller SD. 2005. Toward improving estimates of remotely sensed precipitation with MODIS/AMSR-E blended data techniques. *IEEE Transactions on Geoscience and Remote Sensing* **43**: 1059–1069.
Turk J, Vivekanandan J, Lee T, Durkee P, Nielsen K. 1998. Derivation and applications of near-infrared cloud reflectances from GOES-8 and GOES-9. *Journal of Applied Meteorology* **37**: 819–831.
Turner J, Allam R, Maine D. 1986. A case study of the detection of fog at night using channels 3 and 4 on the Advanced Very High Resolution Radiometer (AVHRR). *Meteorological Magazine* **115**: 285–290.
Turquety S, Hurtmans D, Hadji-Lazaro J, Coheur PF, Clerbaux C, Josset D, Tsamalis C. 2009. Tracking the emission and transport of pollution from wildfires using the IASI CO retrievals: analysis of the summer 2007 Greek fires. *Atmospheric Chemistry and Physics* **9**: 4897–4913.
Twomey S, Cocks T. 1989. Remote sensing of cloud parameters from spectral reflectance in the near-infrared. *Beiträge zur Physik Atmosphäre* **62**: 172–179.
Twomey SA, Piepgrass M, Wolfe TL. 1984. An assessment of the impact of pollution on global cloud albedo. *Tellus* **36B**: 356–366.
Twomey S, Seton KJ. 1980. Inferences of gross microphysical properties of clouds from spectral reflectance measurements. *Journal of the Atmospheric Sciences* **37**: 1065–1069.
Urban J, Pommier M, Murtagh DP, Santee ML, Orsolini YJ. 2009. Nitric acid in the stratosphere based on Odin observations from 2001 to 2007-Part 1: a global climatology. *Atmospheric Chemistry and Physics* **9**: 7045–7052.
Valks P, Loyola D. 2008. *Algorithm theoretical basis document for GOME-2 total column products of ozone, minor trace gases, and cloud properties (GDP 4.2 for O3M-SAF OTO and NTO)*. Report DLR/GOME-2/ATBD/01, Remote Sensing Institute – German Aerospace Center (IMF-DLR): Oberpfaffenhofen; 36 pp.
Varnai T, Marshak A. 2002. Observations of three-dimensional radiative effects that influence MODIS cloud optical thickness fields. *Journal of the Atmospheric Sciences* **59**: 1607–1618.
Vaughan MA, Powell KA, Kuehn RE, Young SA, Winker DM, Hostetler CA, Hunt WH, Liu Z, McGill MJ, Getzewich BJ. 2009. Fully automated detection of cloud and aerosol layers in the CALIPSO lidar measurements. *Journal of Atmospheric and Oceanic Technology* **26**: 2034–2050.
Vaughan M, Young S, Winker D, Powell K, Omar A, Liu Z, Hu Y, Hostetler C. 2004. Fully automated analysis of spacebased lidar data: an overview of the CALIPSO retrieval algorithms and data products. *Proceedings of the SPIE* **5575**: 16–30.
Veefkind JP, de Leeuw G. 1998. A new algorithm to determine the spectral aerosol optical depth from satellite radiometer measurements. *Journal of Aerosol Science* **29**: 1237–1248.
Velden CS. 1989. Observational analyses of North Atlantic tropical cyclones from NOAA polar-orbiting satellite microwave data. *J. Appl. Meteorol.* **28**: 59–70.
Velden CS, Goodman BM, Merrill RT. 1991. Western North Pacific tropical cyclone intensity estimation from NOAA polar-orbiting satellite microwave data. *Monthly Weather Review* **119**: 159–168.
Velden CS, Olander TL, Wanzong S. 1998. The impact of multispectral GOES-8 wind information on Atlantic tropical cyclone track forecasts in 1995. Part I: dataset methodology, description, and case analysis. *Monthly Weather Review* **126**: 1202–1218.
Velden CS, Smith WL. 1983. Monitoring tropical cyclone evolution with NOAA satellite microwave observations. *Journal of Applied Meteorology and Climate* **22**: 714–724.
Velden CS, Young JA, Nieman SJ, Menzel WP, Wanzong S, Goerss JS. 1997. Upper-tropospheric winds derived from geostationary satellite water vapor observations. *Bulletin of the American Meteorological Society* **78**: 173–195.
Vicente GA, Scofield RA, Menzel WP. 1998. The operational GOES infrared rainfall estimation technique. *Bulletin of the American Meteorological Society* **79**: 1883–1898.
Viollier M, Standfuss C, Chomette O, Quesney A. 2009. Top-of-atmosphere radiance-to-flux conversion in the SW domain for the ScaRaB-3 instrument on Megha-Tropiques. *Journal of Atmospheric and Oceanic Technology* **26**: 2161–2171.
Von Ahn JM, Sienkiewicz JM, Chang PS. 2006. The operational impact of QuikSCAT winds at the NOAA Ocean Prediction Center. *Weather and Forecasting* **21**: 523–539.
Wagner T, Heland J, Zoger M, Platt U. 2003. A fast H2O total column density product from GOME-Validation with in-situ aircraft measurements. *Atmospheric Chemistry and Physics* **3**: 651–663.
Walton C. 1988. Nonlinear multichannel algorithms for estimating sea surface temperature with AVHRR satellite data. *Journal of Applied Meteorology* **27**: 115–124.
Wan Z, Zhang Y, Zhang Q, Li ZL. 2004. Quality assessment and validation of the MODIS global land surface temperature. *International Journal of Remote Sensing* **25**: 1261–1274.
Wang DY, Höpfner M, Blom CE, Ward WE, Fischer H, Blumenstock T, Hase F, Keim C, Liu GY, Mikuteit S, Oelhaf H, Wetzel G, Cortesi U, Mencaraglia F, Bianchini G, Redaelli G, Pirre M, Catoire V, Huret N, Vigouroux C, De Maziére M, Mahieu E, Demoulin P, Wood S, Smale D, Jones N, Nakajima H, Sugita T, Urban J, Murtagh D, Boone CD, Bernath PF, Walker KA, Kuttippurath J, Kleinböhl A, Toon G, Piccolo C. 2007. Validation of MIPAS HNO3 operational data. *Atmospheric Chemistry and Physics* **7**: 4905–4934.
Warner JX, Wei Z, Strow LL, Barnet CD, Sparling LC, Diskin G, Sachse G. 2010. Improved agreement of AIRS tropospheric carbon monoxide products with other EOS sensors using optimal estimation retrievals. *Atmospheric Chemistry and Physics* **10**: 9521–9533.
Waters JW, Froidevaux L, Harwood RS, Jarnot RF, Pickett HM, Read WG, Siegel PH, Cofield RE, Filipiak MJ, Flower DA, Holden JR, Lau GK, Livesey NJ, Manney GL, Pumphrey HC, Santee ML, Wu DL, Cuddy DT, Lay RR, Loo MS, Perun VS, Schwartz MJ, Stek PC, Thurstans RP, Boyles MA, Chandra KM, Chavez MC, Chen GS, Chudasama BV, Dodge R, Fuller RA, Girard MA, Jiang JH, Jiang Y, Knosp BW, LaBelle RC, Lam JC, Lee KA, Miller D, Oswald JE, Patel NC, Pukala DM, Quintero O, Scaff DM, Van Snyder W, Tope MC, Wagner PA, Walch MJ. 2006. The Earth Observing System Microwave Limb Sounder (EOS MLS) on the aura satellite. *IEEE Transactions on Geoscience and Remote Sensing* **44**: 1075–1092.
Waters JW, Read WG, Froidevaux I, Jarnot RF, Cofield RE, Flower DA, Lau GK, Pickett HM, Santee ML, Wu DL, Boyles MA, Burke JR, Lay RR, Loo MS, Livesey NJ, Lungu TA, Manney GL, Nakarnura LL, Perun VS, Ridenoure BP, Shippony Z, Siegel PH, Thurstans RP. 1999. The UARS and EOS Microwave Limb Sounder (MLS) experiments. *Journal of the Atmospheric Sciences* **56**: 194–218.
Watson IM, Realmuto VJ, Rose WI, Prata AJ, Bluth GJS, Gu Y, Bader CE, Yu T. 2004. Thermal infrared remote sensing of volcanic emissions using the moderate resolution imaging spectroradiometer. *Journal of Volcanology and Geothermal Research* **135**: 75–89.
Wei C, Hung WC, Cheng KS. 2006. A multi-spectral spatial convolution approach of rainfall forecasting using weather satellite imagery. *Advances in Space Research* **37**: 747–753.
Weissman DE, Bourassa MA, O'Brien JJ, Tongue JS. 2003. Calibrating and validating the QuikSCAT/Sea Winds radar for measuring rain rate over the ocean. *IEEE Transactions on Geoscience and Remote Sensing* **41**: 2814–2820.
Weisz E, Li J, Li J, Zhou DK, Huang HL, Goldberg MD, Yang P. 2007. Cloudy sounding and cloud-top height retrieval from AIRS

alone single field-of-view radiance measurements. *Geophysical Research Letters* **34**: L12802.

Weng F, Grody NC. 1994. Retrieval of cloud liquid water using the special sensor microwave imager (SSM/I). *Journal of Geophysical Research* **99**: 25535–25552.

Weng F, Grody NC. 2000. Retrieval of ice cloud parameters using a microwave imaging radiometer. *Journal of the Atmospheric Sciences* **57**: 1069–1081.

Weng FW, Zhao L, Ferraro R, Poe G, Li X, Grody NC. 2003. Advanced Microwave Sounding Unit (AMSU) cloud and precipitation algorithms. *Radio Science* **38**: 8068–8083.

Wenig M, Kühl S, Beirle S, Bucsela E, Jähne B, Platt U, Gleason J, Wagner T. 2004. Retrieval and analysis of stratospheric NO from GOME. *Journal of Geophysical Research* **109**: D04315.

Wentz FJ. 1983. A model function for ocean microwave brightness temperatures. *Journal of Geophysical Research* **88**: 1892–1908.

Wentz FJ. 1997. A well-calibrated ocean algorithm for special sensor microwave imager. *Journal of Geophysical Research* **102**: 8703–8718.

Wentz FJ, Gentemann C, Smith D, Chelton D. 2000. Satellite measurements of sea surface temperature through clouds. *Science* **288**: 847–850.

Wentz FJ, Meissner TF. 2000. *Algorithm Theoretical Basis Document (ATBD): version 2: AMSR ocean algorithm*. RSS Technical Proposal 121599A-1, Remote Sensing Systems: Santa Rosa, CA; 59 pp.

Wespes C, Hurtmans D, Clerbaux C, Santee ML, Martin RV, Coheur PF. 2009. Global distributions of nitric acid from IASI/MetOP measurements. *Atmospheric Chemistry and Physics* **9**: 7949–7962.

Wielicki BA, Barkstrom BR, Harrison EF, Lee RB III, Smith GL, Cooper JE. 1996. Cloud and the Earth's Radiant Energy System (CERES): an Earth observing system experiment. *Bulletin of the American Meteorological Society* **77**: 853–868.

Wielicki BA, Coakley JA. 1981. Cloud retrieval using infrared sounder data: error analysis. *Journal of Applied Meteorology* **20**: 157–169.

Wilheit T, Adler R, Avery S, Barrett E, Bauer P, Berg W, Chang A, Ferriday J, Grody N, Goodman S, Kidd C, Knieveton D, Kummerow C, Mugnai A, Olson W, Petty G, Shibata A, Smith E. 1994. Algorithms for the retrieval of rainfall from passive microwave measurements. *Remote Sensing Reviews* **11**: 163–194.

Wilheit TT, Chang ATC. 1980. An algorithm for retrieval of ocean surface and atmospheric parameters from the observations of the Scanning Multichannel Microwave Radiometer (SMMR). *Radio Science* **15**: 525–544.

Wind G, Platnick S, King MD, Hubanks PA, Pavolonis MJ, Heidinger AK, Yang P, Baum BA. 2010. Multilayer cloud detection with the MODIS near-infrared water vapor absorption band. *Journal of Applied Meteorology and Climatology* **49**: 2315–2333.

Winker DM, Hunt WH, McGill MJ. 2007. Initial performance assessment of CALIOP. *Geophysical Research Letters* **34**: L19803.

Winker DM, Vaughan MA, Omar A, Hu Y, Powell KA, Liu Z, Hunt WH, Young SA. 2009. Overview of the CALIPSO mission and CALIOP data processing algorithms. *Journal of Atmospheric and Oceanic Technology* **26**: 2310–2323.

Wittrock F, Richter A, Oetjen H, Burrows JP, Kanakidou M, Myriokefalitakis S, Volkamer R, Beirle S, Platt U, Wagner T. 2006. Simultaneous global observations of glyoxal and formaldehyde from space. *Geophysical Research Letters* **33**: L16804.

Wong E, Hutchison KD, Ou SC, Liou KN. 2007. Cirrus cloud top temperatures retrieved from radiances in the National Polar-Orbiting Operational Environmental Satellite System – Visible Infrared Imager Radiometer Suite 8.55 and 12.0 μm bandpasses. *Applied Optics* **46**: 1316–1325.

Wu R, Weinman JA, Chin RT. 1985. Determination of rainfall rates from GOES satellite images by a pattern recognition technique. *Journal of Atmospheric and Oceanic Technology* **2**: 314–330.

Wydick JE, Davis PA, Gruber A. 1987. *Estimation of broadband planetary albedo from operational narrowband satellite measurements*. Technical Report NESDIS 27, NOAA: Washington, DC; 32 pp.

Wylie DP. 1979. An application of a geostationary satellite rain estimation technique to an extra-tropical area. *Journal of Applied Meteorology* **18**: 1640–1648.

Wylie DP, Menzel WP. 1999. Eight years of cloud statistics using HIRS. *Journal of Climate* **12**: 170–184.

Wylie DP, Menzel WP, Strabala KI. 1994. Four years of global cirrus cloud statistics using HIRS. *Journal of Climate* **7**: 1972–1986.

Xiong X, Barnet C, Maddy E, Sweeney C, Liu X, Zhou L, Goldberg M. 2008. Characterization and validation of methane products from the Atmospheric Infrared Sounder (AIRS). *J. Geophys. Res.* **113**: G00A01.

Yan H, Yang S. 2007. AMODIS dual spectral rain algorithm. *Journal of Applied Meteorology and Climatology* **46**: 1305–1323.

Yang K, Krotkov NA, Krueger AJ, Carn SA, Bhartia PK, Levelt PF. 2007. Retrieval of large volcanic SO2 columns from the aura ozone monitoring instrument: comparison and limitations. *Journal of Geophysical Research* **112**: D24S43.

Yoshida R, Okamoto H, Hagihara Y, Ishimoto H. 2010. Global analysis of cloud phase and ice crystal orientation from Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) data using attenuated backscattering and depolarization ratio. *Journal of Geophysical Research* **115**: D00H32.

Young DF, Minnis P, Baumgardner D. 1998. Comparison of in situ and satellite-derived cloud properties during SUCCESS. *Geophysical Research Letters* **25**: 1125–1128.

Yu TW, Iredell M, Keyser D. 1997. Global data assimilation and forecast experiments using SSM/I wind speed data derived from a neural network algorithm. *Weather and Forecasting* **12**: 859–865.

Yu H, Kaufman YJ, Chin M, Feingold G, Remer LA, Anderson TL, Balkanski Y, Bellouin N, Boucher O, Christopher S, DeCola P, Kahn R, Koch D, Loeb N, Reddy MS, Schulz M, Takemura T, Zhou M. 2006. A review of measurement-based assessments of the aerosol direct radiative effect and forcing. *Atmospheric Chemistry and Physics* **6**: 613–666.

Yu YY, Privette JL, Pinheiro AC. 2005. Analysis of the NPOESS VIIRS land surface temperature algorithm using MODIS data. *IEEE Transactions on Geoscience and Remote Sensing* **43**: 2340–50.

Yu T, Rose WI. 2000. Retrieval of sulfate and silicate ash masses in young (1–4 d old) eruption clouds using multi-band infrared HIRS/2 data. In *Remote Sensing of Active Volcanism*, *Geophysical Monograph Series, Vol. 116*, Mouginis-Mark P, Crisp J, Fink J (eds). AGU: Washington, DC; 87–100.

Zhang T, Wen J, van der Velde R, Meng X, Li Z, Liu Y, Liu R. 2008. Estimation of the total atmospheric water vapor content and land surface temperature based on AATSR thermal data. *Sensors* **8**: 1832–1845.

Zhang W, Xu J, Dong C, Yang J. 2006. China's current and future meteorological satellite systems. *Earth Science Satellite Remote Sensing*, *Science and Instruments*. Springer: Berlin; 392–413.

Zhao L, Weng F. 2002. Retrieval of ice cloud parameters using the advanced microwave sounding unit. *Journal of Applied Meteorology* **41**: 384–395.

Zuidema P, Joyce R. 2008. Water vapor, cloud liquid water paths, and rain rates over northern high latitude open seas. *Journal of Geophysical Research* **113**: D05205.

